THEORY AND OPERATION OF THE FOURDRINIER PAPER MACHINE

G. H. NUTTALL

701

THEORY AND OPERATION
OF THE FOURDRINIER
PAPER MACHINE

THEORY AND OPERATION OF THE FOURDRINIER PAPER MACHINE

BY

G. H. NUTTALL, M.A. (Cantab.)

CONTENTS

PART 3: THE WIRE SECTION

PART 4: THE PRESS SECTION

PART 5: THE DRYING SECTION AND CALENDERS

PART 6: PRODUCTION CONTROL

FOREWORD

This book has been written primarily for persons who are, or hope to be, directly concerned with the production of paper or with technical aspects of papermaking. It assumes some basic knowledge and a fair degree of familiarity with paper machines. The intention has been to provide a comprehensive background of information which can be readily referred to, but is at the same time sufficiently readable to serve as a text book for advancing knowledge of the process. In scope it fills a gap between general introductory books on papermaking and the large reference works which are mainly concerned with giving a detailed description of the various types of equipment available. When supplemented with practical experience and an intimate knowledge of the particular machine under his charge, it should assist the operator and supervisor to use the equipment in a systematic and informed manner and obtain the best performance from it.

The book is divided into six parts. The first five of these deal with separate sections of the Fourdrinier paper machine: 1, the wet-end flow system; 2, screens and cleaners; 3, the wire part; 4, the press section; and 5, the dryers and calenders. Each of these parts is divided into three main chapters. The first chapter describes theoretical aspects of the process as derived from the results of research work. This material is presented as simply as possible, but to avoid undue length it is assumed that the reader has some familiarity with graphical presentation and a basic knowledge of physics. The approach adopted is essentially descriptive rather than analytical and is not intended as a detailed and exhaustive survey. Rather the object is to give a general background of fundamental principles so far as they are known, and then discuss their relevance and importance to efficient operation.

The second chapter of each part concerns operational aspects of the paper machine and details the various factors which can affect and upset the process. Particularly in these chapters the results of experimental work, for the most part reported in papermaking literature, have been freely drawn on and interpreted in the light of theoretical considerations. An attempt is made to place into perspective the influence of different operational variables associated with running a paper machine in order to indicate how best various quality requirements can be fulfilled and the whole operation brought under more efficient control. Inevitably this involves making comparisons between different designs of equipment but to ensure that such remarks are as impartial as possible reliance is placed almost entirely on published reports and experimental comparisons; any comments based on personal experience or manufacturers' pamphlets are carefully identified.

The third chapter of each part is concerned entirely with practical

ix

aspects of paper machine operation. The value and use of process instrumentation and controls are discussed, maintenance requirements are detailed, and the main tasks of machine crews are described with particular emphasis on the problems of running the machine to produce a consistent product. In this respect the requirements for making periodic comprehensive checks through the machine system are given special attention because it is considered that these provide an essential background of information for successful long-term operation. There is also some discussion of the basic practical tasks involved in machine operation but in this no attempt is made to be thorough and only certain common, and in most cases to the experienced man doubtless commonplace, principles are stated. The usual topics of start-up and shut-down routines are covered briefly and consideration is also given to discussing what to pay attention to when operation is proceeding smoothly. Practical knowledge must be acquired by actually running a paper machine, and the remarks in these particular sections give only a general background against which to relate the characteristics and peculiarities of any individual machine.

Part 6 is concerned with methods of monitoring the performance of paper machines and describes the operating data required if adequate financial control is to be achieved. This subject, which comes under the broad heading of Production Control, is one that has been rather neglected especially in relation to making a comparison of the profitability of running different grades on a machine, and indeed of running a single grade at different speeds. These highly important questions are discussed in some detail, and other equally interesting topics such as the costing of improvements in machine operation and assessing the economic benefit from installing new equipment are also covered.

This book, then, is concerned with running a paper machine to achieve the best possible performance. The machine itself, and the ancillary equipment and instrumentation associated with it, are not described in any detail except for a few less well-known items where a brief description appeared necessary for clarification. If the reader requires information about the design and basic operation of papermaking machinery he should refer to the listed references or to one of the several standard text books in which this subject is already well covered. Units throughout are English, unless otherwise stated.

Most of the contents have already appeared in *The Paper Maker* during the period from September 1962 to April 1967. For publication in the present book form the material has been substantially revised and brought up-to-date to include references appearing in papermaking literature up to the end of 1966. References earlier than 1950 have generally not been consulted except in a few specific cases, but when appropriate use has been made of information in several books, particularly the following:—

R. H. Clapperton and W. Henderson. *Modern Paper Making*. Waverley Book Co. Ltd. 1952.

J. N. Stephenson (ed.). *Pulp and Paper Manufacture*, Vol. III. McGraw Hill Book Co. Inc. 1953.

To the authors of these books, and of the many references quoted in the body of this book, due acknowledgement is given.

Lastly the author must record his tremendous debt to the many people who, directly or indirectly, have contributed to this book. This applies first to the Editor and Associate Editor of *The Paper Maker*, Stuart Don and Jack Elliott, who by their interest and encouragement over the years transformed a plan for a few articles on papermaking into a full-scale project with the present book as its objective. Then, as regards the material, the author wishes to record his deep gratitude to those people from whom he has learnt so much of the real practice of papermaking, particularly the Dixon family and colleagues at the Grimsby mill of Peter Dixon and Son Ltd., especially Martin Armitage, Dick Arnett, Bill Harrod and Bill Ross. The greater proportion of information in the book concerning the actual practical operation of paper machines has come from day-to-day discussion of production problems with associates at Dixons.

Finally, a special debt of gratitude is due to three people who have devoted much time and effort to reading through parts of the manuscript and making numerous suggestions and corrections: Jim Burton, Works Manager at Culter Mills, Peterculter, Aberdeenshire, who provided much information and support in the early days of preparation; Tony Truman, Assistant Research Manager at Kearsley Mill, Stoneclough, Lancashire, who has closely vetted the theoretical and technological sections, and in the process revealed a considerable talent as a proof reader; and Bob Fyfe, Chief Papermaker at Oughtibridge Mill, Yorkshire, whose more recent forthright comments created trouble with corrections at the printers. The author is also grateful to two persons who made valuable additions to Part 6 of the book: Alan Marriott of Kimberley-Clark, Ltd., Larkfield, Kent and Ian Kenworthy of the British Paper and Board Industry Research Association, now the Paper and Board, Printing and Packaging Industries Research Association, at Kenley, Surrey. To these friends must go a great deal of credit for this book. It is a reflection on the bond of interest which throws members of the paper industry together that they were willing to spend so much of their leisure time in the arduous and difficult task of reading the material through with a critical eye.

.

THE WET-END FLOW SYSTEM

INTRODUCTION

1I The Fourdrinier machine as a process for making paper may conveniently be regarded as commencing at the machine chest. Up to this point the stuff has been suitably prepared from pulp by beating, refining and blending of different furnishes, and as a general rule the fibre receives no further treatment. The machineman takes over complete responsibility for the process at the machine chest, his primary object then being to form and dry the sheet of paper; the characteristics of that sheet are largely determined by the treatment the fibre has received in the preparation stage so the major requirement of the paper machine system is to produce the sheet at the desired substance and moisture content with, in the general sense of the terms, a suitable finish and as good a formation as possible. By the time the fibre suspension has reached the slice the most critical aspects of this task are settled, certainly with regard to substance and to a large extent also with regard to formation. It is this important part of the process, from the machine chest to the slice, that forms the subject of Part 1 of this book.

It is not intended to cover completely the various pieces of equipment which are found between the machine chest and the slice; in particular, the cleaning and screening of paper stock is not dealt with and consistency regulation is only touched upon in passing. On the other hand the backwater system, in its complete sense, and to a lesser degree the broke system are considered, as also is the question of retention in the wire section. Each of these subjects has some bearing on the manner in which the stock feeding the breast box and slice is constituted and as such can affect the making of the sheet and the substance of the paper. The various factors affecting the substance of the paper both along and across the machine are all treated in detail but the formation of the sheet is only considered in so far as it is influenced directly by the condition of the stock leaving the slice. (Thus, the characteristics and angle of flow of stock from the slice are dealt with but the conditions on the wire following impingement are left to Part 3; the overall consistency and condition of the backwater passing through the wire are considered but not the details of drainage).

The general function of the wet-end flow system is to receive stuff from the machine chest at a relatively high consistency, dilute it and lead it to the slice in such a manner that a satisfactory sheet can be made on the wire. The total dry weight of the paper must be correct and steady and this is dependent on the various flows and consistencies which constitute the wet-end and also on the general retention conditions on the wire. The profile of the dry weight of the paper across the machine must also be even and this depends almost entirely on uniformity of the fibre flow and velocity from the slice; the efficiency with which this is achieved is in turn

3

dependent essentially on the approach flow and breast box design. Apart from these requirements the flow leaving the slice should ideally carry fibres evenly dispersed throughout its volume, not flocculated in any way nor (except for some special paper property) aligned in any preferential direction; this is generally considered one of the most difficult objectives to achieve and requires just the right degree of small-scale turbulence at the slice. With all these conditions adequately fulfilled the task of forming the sheet, though still very dependent on having the correct velocity relation between the slice flow and the wire and on suitable controlling of the drainage conditions on the wire, is well on the way to completion.

1I.1 Terminology

It is necessary to use several terms in the following pages which are neither adequately defined nor used in exactly the same sense in different paper-making circles. There is also a difference between the common terminology in use in this country and on the continent of North America. For this reason the author decided to standardize on the same terms throughout and these have been selected with the object of avoiding confusion and ambiguity in the mind of the reader.

'Head box' is used in papermaking literature to refer both to a high-level box for constant-gravity feed of stuff to the machine, and also as the name of the box situated above the slice. This term will therefore be avoided and for the first function 'stuff box' will be adopted ('service box' has the same meaning, but the terms 'mixing box' or 'regulating box' are only used when, in addition to providing a constant head, the thick stuff is diluted in the box); for the second function the old term 'breast box' will be used since this to the papermaker is more familiar than the alternative name 'flow box.'

In systems using a pump for mixing and providing a pressure for feeding the breast box the term 'mixing pump' will be used in preference to 'fan pump' or 'stock pump' since it gives a clear indication of the position of the pump in the wet-end flow system and emphasizes its function as a replacement of the mixing box; it also allows 'fan pump' or 'feed pump' to be applied to a second pump when this is used to take stock from the cleaners to feed the breast box.

In the breast box one piece of equipment has received a plethora of designations: 'evener roll,' 'distributor roll,' 'holey roll,' 'monkey roll,' 'hog roll,' and 'perforated roll' are all in common use. The latter term, 'perforated roll,' seems to strike a balance between the familiar and the presumptuous and will be the one adopted.

Finally, 'backwater system' will be used to refer to the flow of stock drawn through the wire when it is used directly on the machine; 'white-water system' will be used to describe the excess flow which is pumped out of the wire system either to a temporary storage tank for feeding consistency regulators, beaters or hydrapulpers in the preparation plant or directly to a clarifier or save-all. 'Stuff' refers to the fibre suspension in the machine chest at a consistency of 3 per cent. or more; 'stock' to the

diluted suspension feeding the breast box at consistencies usually under 1 per cent.

Consistencies are always understood to refer to bone-dry values, never air-dry since this can too easily lead to error and confusion. Loading or ash content is most conveniently represented as a percentage of the total solids.

THEORETICAL CONSIDERATIONS

1A.1 FLOW OF FIBRE SUSPENSIONS

Though seldom a subject of direct concern to the papermaker, it is desirable to have some idea of the manner in which fibre suspensions flow. This is particularly important for understanding the formation of fibre flocculation and also for a critical examination of the approach flow and breast box design. The general arrangement and sizing of pipes and channels at the wet-end is frequently rather crude when looked at from the viewpoint of papermaking requirements and often unnecessary power loss and aeration may occur; a knowledge of the particular characteristics of the flow of fibre suspensions as compared with other liquids is helpful when considering such aspects as these.

It is proposed firstly to discuss briefly the way in which water flows and then to describe the modification caused by the presence of fibres and the manner in which individual fibres are carried in the flow. The question of frictional resistance to flow and the development and breaking down of fibre flocs will next be dealt with, leading to a discussion of the flow velocities desirable for the various parts of the wet-end system. Brief mention will also be made of the relationship between pressure and flow velocity with, finally, a few points on centrifugal pumps.

1A.1 1 Effect of velocity on the pattern of water flow

At very low velocities the flow of water in a pipe is streamlined. This implies that each particle of water follows directly behind the one in front and keeps in exactly the same relative position in the cross-section of the pipe, all the flow streams being parallel to the pipe axis. On entering a pipe the velocities of the flow streams are at first uniform throughout the pipe cross-section. But at the wall of the pipe friction affects the velocity of the flow and slippage occurs between one streamline and the next. The region in which this happens is known as the boundary layer and as the water travels down the pipe this layer gradually grows to influence more and more of the streamlines. Eventually the boundary layer converges to the centre of the pipe and embraces the entire flow; under this condition the flow pattern is in equilibrium and the velocity of the streamline varies ideally in a parabolic relation from zero at the wall of the pipe to a maximum in the centre. In this type of flow, known as laminar flow, the pressure drop or friction loss along the pipe is proportional to the velocity. Fig. **1.1** illustrates the changing velocity profile and growing boundary layer in the pipe.

As the quantity of water flowing through the pipe is increased the laminar pattern gradually begins to break down. Instead of the flow keeping strictly parallel to the pipe, eddies begin to form in the centre

of the pipe so that the velocity there fluctuates from one moment to the next. With further increase in the average flow velocity the influence of the eddies grows and the flow pattern passes through a transitional stage until it becomes fully turbulent. In this condition, which is the most usual in all practical engineering applications, the velocity of flow, though fluctuating from one instant to the next, is practically the same on average throughout the pipe cross-section with only a slight increase from the wall to the centre. The true boundary layer where the flow is still effectively laminar becomes confined to a narrow region close to the pipe wall. Because of the energy loss in eddies the pressure loss along the pipe is much greater than in laminar flow and becomes approximately proportional to the square of the velocity.

These changing patterns of flow in a pipe apply to all homogeneous fluids and the point at which laminar flow begins to break down is known as the critical velocity; this velocity varies inversely with the diameter of
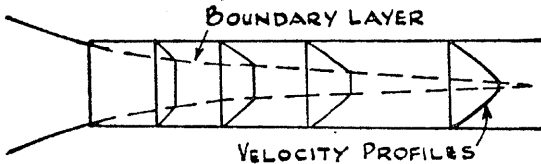
Fig. 1.1. Growth of boundary layer and change in velocity profile of water entering a pipe at very low velocity

the pipe and the density of the fluid and is proportional to the viscosity. A dimensionless number formed by taking the product of the velocity, pipe diameter and density of the fluid and dividing by the viscosity has the same value of approximately 2,000 at the critical velocity for all fluids flowing in a pipe. This expression, termed the Reynold's number, is very useful for comparing the behaviour of different fluids under different conditions and predicting when the flow pattern changes.

1A.1 2 Modification to flow pattern produced by fibre

When fibre is introduced into water the flow patterns that have been described are greatly modified. The work of Robertson and Mason (26, 32, 37) contributed most to an understanding of this and what follows derives largely from their work. Even at very low consistencies of less than 0·05 per cent. the presence of the fibre destroys the homogeneity of the fluid and considerably restricts the freedom of movement of individual water particles. This effect is most marked at very low velocities through a pipe when the whole mass moves along the pipe almost as a solid body. This is known as plug flow and in this state is virtually no relative movement over the whole cross-section of the pipe, the velocity at all points being the same apart from a small boundary layer at the pipe wall where the velocity drops to zero. The boundary layer is free of fibres except at extremely low velocities where small flocs of fibres appear to gather in the layer and roll along the wall. This form of flow is very similar to that for

7

water entering a pipe at low velocity before the boundary layer has spread inward in the manner described above, and it may be considered that the presence of fibre permanently inhibits the normal development of the boundary layer.

As the flow velocity is increased a point is reached where the fibre-free wall layer becomes unstable and a turbulent annulus is formed round the plug. Further increase of the velocity causes progressive enlargement of this annulus and disintegration of the plug until a point is reached where the flow becomes completely turbulent.

Apart from changing the pattern of flow with increasing velocity the presence of fibre substantially alters the frictional resistance and pressure
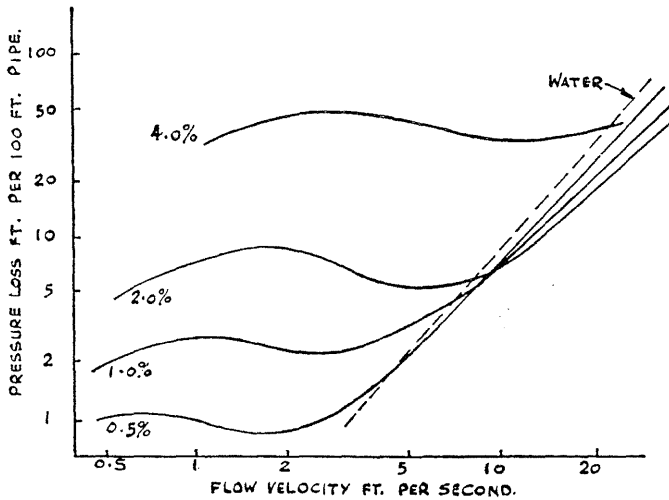
Fig. 1.2. Pressure loss at different flow velocities and consistencies in a pipe

loss for flow in a pipe. At low velocities the pressure loss is greater for fibre suspensions than for water and the higher the consistency, the greater the difference becomes. However, with increasing pipe velocity the presence of fibre also appears to delay the onset of completely turbulent conditions in which the pressure loss increases with velocity at a much higher rate, with the result that a point is reached where the pressure losses are actually lower than for pure water. With further velocity increases in the turbulent region the energy losses occurring continue to be slightly lower than for water and this is thought to be due to a reduction in the scale of turbulence caused by the presence of fibres. Under normal papermaking conditions velocities in pipelines are in the turbulent region and the head loss is roughly proportional to the square of the flow velocity as with water; for consistencies under about 1 per cent. the general characteristics of flow in the turbulent region are in fact very similar to water.

The relationship between pressure loss and flow velocity is illustrated in Fig. 1.2, which shows the sort of results that have been obtained for

fibre suspensions at different consistencies. The curves are drawn from some graphs given by Bonnington (35) in a survey of frictional losses in pipes carrying pulp. It will be observed that the pressure loss over part of the curves actually shows a decrease with increasing velocity; this is characteristic of fibre suspensions and is considered to be due to friction changes in the plug flow region as the layer close to the pipe wall becomes fibre-free and alters in thickness. However, a precise relation with the changing patterns of flow described above has not yet been satisfactorily obtained. The actual velocities and pressure losses depicted in Fig. 1.2 can only be taken as illustrative because both Robertson and Mason (32) and Bonnington (35) emphasize that pipe flow data from various sources, though extensive, is highly contradictory. Changes in pressure losses under different conditions do not agree when the Reynolds numbers are the same, as with water, but are apparently influenced considerably by the characteristics of the fibres in suspension. The peculiarities of fibre flow which can lead to such phenomena as stapling and collecting on sharp edges and the tendency to settle and coalesce at low velocities also complicate the picture. The formation of flocs of fibres has a particularly important relation with the flow pattern and this will now be discussed.

1A.1 3 Flow of individual fibres and flocculation

In an experiment using rigid and uniform acrylic fibres at low concentration in a tube, Baines and Nichol (22) established that in slow laminar flow the fibres have a tendency to align close to the streamlines with small oscillations about this orientation. With the onset of turbulence at greater flow velocities, fibre orientation in the flow becomes random, though near to the wall of the tube a preference for alignment along the wall persists. In a region of contraction with flow acceleration the fibres show a tendency to align with the flow even at turbulent velocities. Under all conditions the fibres travel at the same velocity as the flow.

These findings are in broad agreement with earlier results by other workers who have used papermaking fibres under different experimental conditions, though some authors, notably Van den Akker (16), earlier considered that fibre alignment in laminar flow does not occur. In particular, the work of Mason and Robertson (13, 14, 15) showed that in the presence of a simple velocity gradient fibres tend to align more with flow while showing twisting and bending motions round themselves; in turbulent conditions, however, the orientation is random. In normal papermaking, turbulent conditions apply in pipe flow but at the slice the acceleration of flow produces some preferential alignment in the direction of flow; this has been clearly demonstrated by Wrist (74) who found that a degree of fibre orientation in the machine direction exists in the slice jet and is dependent on the consistency of the stock and, to a lesser extent, the type of fibre and design of the slice itself.

The work of Mason and Robertson mentioned above was directed primarily towards gaining an understanding of flocculation and it is in this connection that some interesting facts emerged which have since been

9

verified by Steenberg (92). It appears that flocculation is primarily a mechanical phenomenon occurring when conditions of flow are such that individual fibres are lead to contact each other in a relatively gentle manner. The conditions producing mechanical entanglement are those where mild shear forces exist which allow slow relative motion between individual fibres; while slowly passing each other fibres then have a tendency to entangle and adhere together forming a 'doublet' (the number of doublets formed increasing with time) and some of these may in turn collect further fibres resulting in a growing size of floc. It was also shown that the greater the fibre concentration and the longer the length and greater the flexibility of individual fibres, the more flocculation tends to occur.

This phenomenon is associated with the increase in network strength of the suspension which occurs in these conditions, i.e., in the ability of the fibre mass to resist breaking up under the influence of tensile and shear forces. When subjected to disrupting forces a network of fibres yields in regions where the consistency happens by random chance to be lower than the average; such regions are fewer when the suspension is at a higher concentration or more uniform in structure, in which case in given conditions of shear, the flocs generated will be greater in size.

While promoting flocculation by entanglement of fibres, shear forces act at the same time as a disrupting factor, pulling the flocs apart by causing relative motion between different parts of the floc. In fact, the life of a fibre doublet was shown in the work of Mason and Robertson to be inversely proportional to the shear rate, i.e. the greater the shear rate, the quicker flocs break up. For this reason, individual flocs reach a maximum size in given conditions of turbulence, and also the number of flocs appears to reach a state of dynamic equilibrium in which the rate of formation and disruption becomes equal.

From this explanation it is apparent that conditions in a chest where fibres are kept in suspension by mechanical shear can easily lead to flocculation. The degree of flocculation in pipe flow at low velocities depends very much on the change in flow pattern as the plug flow pertaining under these conditions gradually breaks down. Where flow becomes turbulent, however, the increasing shear forces which occur will rapidly produce dispersion.

In one interesting experiment, using consistencies up to 0·7 per cent., Mason and Robertson confirmed by an optical method of measuring flocculation in a tube that in turbulent flow floc dispersion is promoted by increased flow velocity and hindered by increased consistency. Chemicals such as deacetylated Karaya gum were also investigated and shown to reduce flocculation; their effect was considered to be due to the deposition of a lubricating film on individual fibres. Retention aids and whitewater flocculants such as Sveen glue, activated silica sol, and sodium aluminate have the opposite effect of increasing flocculation but this is thought to be largely an electrolytic action.

The degree of flocculation in stock is ultimately of greatest importance in the slice jet. At this point there are many difficulties in obtaining a satisfactory measure of flocculation though optical methods similar to

those employed by Mason and Robertson have been successfully used by Wrist (74) and, on an actual paper machine, by Beveridge and Bridge (80). Correlation with the formation properties of paper is necessary before this work can be usefully interpreted but the technique is likely to prove valuable in future investigations.

1A.1 4 Desirable flow velocities at the wet-end

If flow velocities of fibre suspensions are low there may be a tendency for flocculation to occur and the fibres may also begin to settle. In addition, because of the increased likelihood of regions where the flow is practically stationary, air bubbles will gather increasingly on the surface producing foam and slime accumulations. On the other hand, if flow velocities are high undue pressure losses will be sustained and there is an increasing chance of pressure fluctuations with surges in flow due to unstable flow separation at bends and valves in the pipework and the presence of excessive eddying in channels and boxes. Further, suction of air into the stock becomes more likely and this can also be very detrimental.

For flow in pipelines the ideal is probably a mildly turbulent condition since this will best avoid the various disadvantages of extremes of low and high velocity. Unfortunately data available for a reasonable estimation of the appropriate velocities under different conditions is, as has already been emphasised, contradictory, and the critical velocities for onset of turbulence are very dependent on fibre characteristics. However, for normal pipelines carrying stock feeding the breast box a reasonable compromise is a flow velocity of between 5 and 10 ft. per second. The relevant flow for pipework is readily calculated from either of these formulae:

$$\text{Flow in pipe in ft./sec.} = \frac{0\cdot49 \times \text{Flow in gallons/min.}}{(\text{Diameter in ins.})^2}$$

$$= \frac{7\cdot66 \times \text{B.D. production in long tons/24 hrs.}}{(\text{Diameter in ins.})^2 \times \text{Consistency}}$$

The latter term assumes no loss or re-circulation of fibre.

For higher consistencies, to achieve the same flow condition requires higher velocities: for 3 per cent. stock between 15 and 20 ft. per second is probably the velocity region which would be needed. But in practice this would lead to very high friction losses and it is not usual to plan for a velocity over about 10 ft. per second. For the stuff pipe feeding a mixing pump, however, it is worth considering another aspect. In this case a predominant requirement is that the flow of fibre down the pipe should be constant. With the pressure difference along the pipe and across the stuff control valve constant, as under given conditions they will be to all intents and purposes, the flow velocity is altered only by a change in consistency producing a different frictional resistance along the pipe. Since a greater consistency increases the pressure loss, the flow is neces- sarily reduced; careful choice of the average velocity down the pipe can

cause the increase in consistency to be closely balanced by the consequent drop in flow, with a net effect on the total flow of fibre which becomes negligible. To achieve this condition it is necessary that an increase in consistency produces a proportionate increase in the total pressure drop. In most installations the stuff control valve will account for over 80 per cent. of the total pressure drop so that the pipe loss must increase by a proportion roughly four or five times larger. It appears from graphs similar to that shown in Fig. 1.2 that this order of change in pressure loss with consistency only occurs in the laminar flow region where the velocity required is rather lower than that producing turbulent conditions. In most cases velocities of about 4 to 5 ft. per second will be fairly close to the ideal; this is lower than is often prefered but the pipe run will generally be vertical and short enough to make it unlikely that settling or flocculation become troublesome. Also with the normal system of feeding from a stuff box it is not necessary to have the box very high to achieve this order of velocity and a further advantage is that the lower pressure loss from pipe friction means that the flow control valve is more sensitive.

For the breast box and pit, particularly the latter, the average flow velocity will be much lower than in other parts of the system and will be dependent on the varying cross-sectional area below the surface level. The flow patterns at different velocities described for pipes cannot be extended to flow under these conditions and fuller discussion is left to the appropriate section later.

1A.15 Relation between pressure and flow

In liquid flow of any kind if pressure losses due to wall friction and turbulence are ignored application of the principle of conservation of energy shows that the total energy compounded of potential energy above a datum line, kinetic energy of flow, and static pressure energy must remain constant. Expressed for convenience in equivalent feet head of liquid this becomes $Z + v^2/2g + P =$ constant, where Z is the height above the datum line in feet, v is the velocity in ft./sec., $g = 32$ and P is the static pressure (relative to atmospheric pressure) in equivalent feet head of the liquid, as would be indicated by an ordinary pressure gauge. This simple formula is very useful when considering changing hydrodynamic conditions and it is necessary to appreciate the implications of it if the significance of pressure gauge readings is to be completely understood.

In the first place it is important to note that a change in level, Z, with everything else constant produces a change in the pressure, p: thus, a rise of 23 ft. in a pipeline with stock flowing through will reduce the reading of a pressure gauge by 10 p.s.i. (1 p.s.i. = 2·3 ft. head water). For a change in velocity, such as occurs with changing area of the cross-section of flow, a similar alteration occurs in the static pressure. For example, an increase in velocity from 8 ft./sec. to 32 ft./sec. caused by halving the diameter of a pipe will produce a decrease of pressure equivalent to 15 ft. of head or 6·5 p.s.i. This phenomenon is used, of course, in orifice and venturi flow meters where measurement of the difference in pressure at two different

flow velocities enables the quantity of flow to be determined. If the cross-section is reduced considerably producing a large increase in flow velocity the static pressure is also considerably reduced and can become lower than atmospheric. This principle is usefully used in the various types of ejector. Normally, however, such a condition is undesirable for two reasons. Expansion of the cross-section after the constriction can cause the flow to separate and leave the wall of the pipe, producing highly unstable conditions with pressure surges down-stream and excessive turbulence. Also if, due to high velocity in the constriction, the pressure in the fluid falls below the vapour pressure at the prevailing temperature, the flow boils and bubbles form which are carried with the stream and collapse when a region of higher pressure is reached; this is known as cavitation and leads to the formation of pressure waves in the fluid as well as producing serious mechanical damage to the pipe wall. Cavitation is more likely to be trouble-some at the suction side of pumps but excessive throttling of valves can also be a cause.

If a flow of water emerges from an orifice into air the static pressure of the liquid becomes zero. Reference to the formula shows that this must be accompanied by an increase in velocity compared to the velocity just inside the orifice where some static pressure can be sustained. If the flow is to keep intact, this in turn implies that the cross-sectional area must diminish in order that the quantity is unaltered. This reduction in the area taken up by the flow is readily observed as a narrowing in the width of a jet issuing from a hole in a tank full of water, and is partly the cause of a growth in instability in the flow as the jet gets further from the hole. A similar phenomenon occurs when stock issues from a slice and one practical significance is that the velocity of the flow at the point of leaving the slice (and also, to a slightly lesser extent, at the point of meeting the wire) is lower than the theoretical velocity which would be achieved if all the pressure head behind the slice were turned into kinetic energy of velocity. The velocity is, therefore, not given simply by the equation $v^2/2g = h$ or $v = \sqrt{2gh}$, where h is the head behind the slice, but a coefficient less than unity, C, must be introduced to take account of the contraction in the jet and also of a slight friction loss, giving $v = C\sqrt{2gh}$. The value of C depends entirely on the geometrical character of the opening: in vertical slices it is between 0·6 and 0·7 but in projection slices it is close to unity. It must also be realised that up to the point where the jet is fully contracted the 'vena contracta,' the velocity is continually increasing so that the velocity of the jet when it lands on the wire is dependent to some extent on the distance it travels. For the purpose of calculation it is normally convenient to refer to the velocity at the orifice rather than the vena contracta in order that calculation of the volume discharge involves a straightforward multiplication by the actual dimensions of the slice opening.

In practice the general equation relating velocity and pressure requires modification due to the fact that energy losses occur from heat generation in turbulence and friction at the pipe walls. This effectively reduces the value of the constant in the equation as the flow progresses through the

system. Pressure losses of water in pipework under different conditions are fairly well known and it has already been mentioned that in the normal turbulent flow the loss increases proportionally to the square of the velocity. Bends, particularly when sharp, tee-junctions, orifices, and especially valves which are used to govern the flow by alteration of the pressure drop across their opening all usually contribute greater head losses in the system than simple pipe losses. For fibre suspensions there is comparatively little data on losses in pipe fittings though at consistencies above 1 per cent. they are likely under normal conditions to be two or three times those for water. Perforated rolls, evener plates and other equipment often found in a breast box all contribute a pressure loss which affects the effective head behind the slice when they are situated close to the slice; this will be considered in greater detail later.

1A.16 Centrifugal pumps

Centrifugal pumps of varying design are the most common type used for providing pressure at the mixing pump. Fig. 1.3 shows the usual sort of
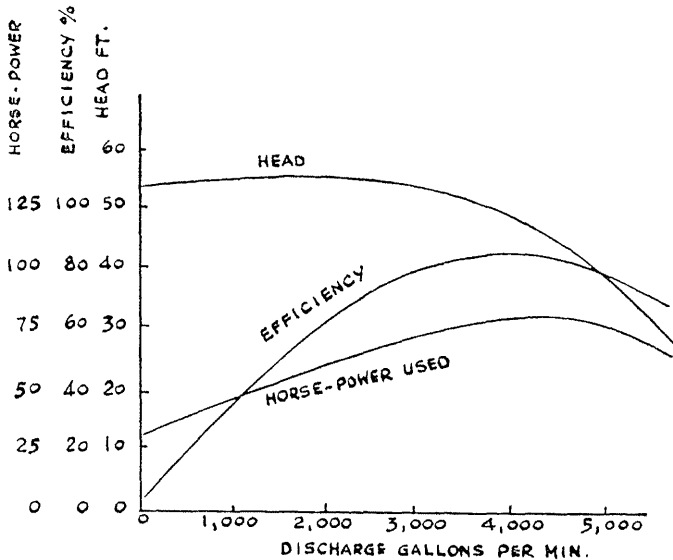
Fig. 1.3. Performance of a typical centrifugal pump with varying water flow

alteration in performance with varying water flow of this type of pump. When pumping fibre suspension, particularly at stuff consistencies, these characteristics are modified considerably and the pressure head and efficiencies are both reduced with increasing consistency. The air content in the suspension also affects the performance appreciably and in extreme

14

cases the pump can, of course, cease to function; for this reason it is always preferable to have the suction side of the pump drowned to reduce the ease with which air can separate out in the pump body.

Partly because of the paucity of reliable data on stuff pump performance the manufacturers have a strong tendency to be on the safe side and supply pump impellers and motors which are amply over-sized. The initial expense is therefore higher than necessary but this is a negligible factor compared to the increased cost of power consumption resulting from a lower running efficiency, and the necessity for heavy throttling on the pump discharge to dissipate a large proportion of the power generated (this increased cost can easily equal the initial cost of the pump within a few months). When faced with an over-powerful pump the simplest answer is usually to substitute a smaller size impeller. Re-circulation of a proportion of the flow permits a reduced pressure drop across the main flow control valve, but apart from the risk of instability if high recirculation flows are used this procedure generally increases power consumption dependent on whereabouts on the pump performance curves the normal running condition is located.

These remarks assume that the motor is a.c. and that control of the flow need not be too critical. At the mixing pump it is far more important to secure a smooth flow and this is closely connected with the method used to control the flow, a topic dealt with in more detail in 1C.1 4. It can be noted here, however, that for this particular application a variable speed drive from a d.c. motor has much to commend it if the supply is available, and the additional expense involved in this is very soon covered by the large power saving possible.

1A.2 INFLUENCE OF WET-END DESIGN ON OPERATIONAL STABILITY

It is often thought that if the flow and the consistency of fresh stuff entering the mixing box or pump at the wet-end is closely controlled then, ignoring moisture differences in the finished paper, the substance will also be closely controlled provided the machine speed and draw are stable. While this is largely true it is only correct up to a point and in this section it is proposed to discuss the various factors which, at least on a theoretical level, can affect the substance of the paper even when the flow and consistency of fresh stuff are perfectly steady. In many paper machine systems some of the points about to be discussed are unlikely to have any great significance, but it is important nonetheless to be aware of the factors that could have a possible influence. Many long-term or cyclic weight fluctuations which defy elimination can be due to unsuspected variations in the backwater and whitewater system and it is the effect of these, and of deliberate alterations made by machinemen in the course of their work, that is now considered. It is likely in the near future that the use of dynamic models of the wet-end flow system in conjunction with analogue and on-line digital computers will bring considerable progress in this field, see for example references 76 and 87.

1A.2 1 Backwater system balance at the wet-end

It is common practice nowadays to use backwater from the wire table rolls and suction boxes to dilute the fresh stuff before it passes to the breast box. It is proposed firstly to consider this particular flow, which for convenience will be referred to as the backwater circuit. This circuit can be thought to have inputs of water and fibre in the form of fresh stuff, and also to a lesser extent in the form of whitewater showers, together with an input of fresh water in breast box and cleaner showers, sealing glands, wire sprays in the main pit, etc. This must be balanced by the water and fibre leaving in the paper passing from the couch, together with the excess backwater which is pumped out of the system and any reject from the cleaners. The excess backwater can be removed either separate from or
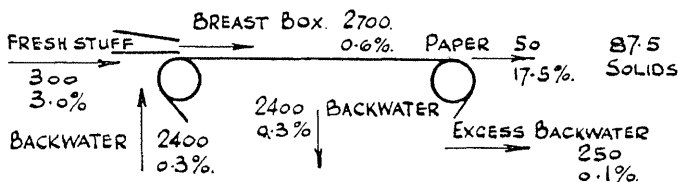
Fig. 1.4. Simple wet-end flow system. Flow volume figures printed above, consistencies below, for each flow

together with the trim from the wire and the wire sprays above the couch pits, but this does not affect the balance in the backwater system, only in the whitewater system and this will be considered later.

It follows that any change occurring in any of these inputs or outputs can affect the fibre and water leaving the system in the paper web and as such can affect the dry weight of the paper. A blocked whitewater shower or a change in the cleaner reject flow to drain could, for example, affect the weight. Apart from the fresh stuff most flows of this nature should be sufficiently steady in practice to be neglected, at least over a relatively short period; the volume of water leaving in the paper will also have a negligible effect on the overall balance, so that the excess backwater should normally have a steady flow when the fresh stuff is also steady. However, the fibre volume leaving in the excess backwater flow will be influenced by any change that may occur in the backwater circuit consistency and this must affect the weight of the paper. Such a change may be deliberate, as when the machineman observes that the sheet appears wetter or freer and alters the amount of 'water on the wire,' i.e. the quantity of backwater in relation to fresh stuff used for mixing, or it may be accidental, as when retention conditions on the wire change. Often, an attempt is made to reduce the influence of these factors by using backwater from the suction boxes preferentially for the excess flow since this is usually at a much lower consistency than the table roll backwater. This expedient, when efficiently carried out, effectively reduces weight variations of a permanent nature due to disturbances in the backwater circuit. However, it is not often realised that considerable transient weight changes are still possible.

16

This can best be illustrated by taking a specific example and for this purpose the simple system fairly typical of a newsprint machine shown in Fig. 1.4 will be used. Flow volume figures are printed above for each flow and may be taken as gallons per minute, consistency figures are printed below. Thus a fresh stuff flow of 300 gallons per minute at 3 per cent. B.D. consistency is diluted at the mixing box or pump by 2,400 gallons per minute of backwater at 0·3 per cent. This produces a flow of 2,700 gallons per minute at 0·6 per cent. consistency at the slice. Retention, defined here in the terms of the consistencies of breast box stock and backwater, is 50 per cent. The volume of water leaving in the paper is 50 gallons per minute at 17·5 per cent. consistency and the excess backwater (assumed to be from the suction boxes) is 250 gallons per minute at a consistency of 0·1 per cent. In terms of solids it is seen that 90 lb. per minute of fresh stuff yield 87·5 lb. per minute of paper with 2·5 lb. per minute of excess backwater flow.

1A.2 2 Alteration in retention conditions

Suppose, firstly, that retention conditions on the wire suddenly alter from 50 per cent. to 33⅓ per cent. The fresh stuff flow remains unchanged, and it is assumed that the effect on the excess backwater consistency, composed largely of suction box water, is negligible. At the time when the retention drops a greater percentage of fibre passes through the wire; it follows that less fibre is couched off the wire and the consistency at the couch reduces together with the dry weight of the paper. This is shown in Fig. 1.5a. The backwater consistency, being higher now, raises the breast box consistency and at the second pass, Fig. 1.5b, raises all the consistencies at the wire and begins to correct the weight of the paper. Fig. 1.5c shows the situation at the third pass and successive passes can be shown to cause a stepped exponential approach in the backwater and breast box consistencies to the final equilibrium conditions shown in Fig. 1.5d.

The ultimate effect of the change in retention is seen, by comparing Figs. 1.4 and 1.5d, to be an increase from 0·3 per cent. to 0·55 per cent. in the backwater consistency and an increase from 0·6 per cent. to 0·82 per cent. in the breast box stock consistency. The weight of the paper has returned from the equivalent of 63·5 solids when the retention first dropped to its original value of 87·5 solids, confirming that in equilibrium conditions if the input and excess backwater fibre are unaltered then the total output is also unchanged. The reduction in fibre passing over the couch at the time the retention dropped, up to the final return to the previous value, has provided the additional fibre in circulation in the backwater system. The reduction in weight refers, of course, to dry weight and if the moisture content of the paper were not controlled the effect on the total substance of the paper may be even greater due to the moisture and dry-weight following each other.

This exercise shows clearly that alteration in retention conditions on the wire will have an effect on the dry weight until equilibrium conditions are re-established. An instantaneous change in retention would require a
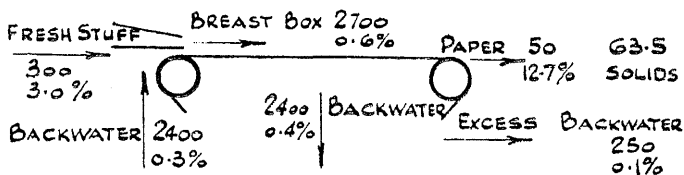
Fig. 1.5a. Retention in system shown in Fig. 1.4 suddenly reduced to $33\frac{1}{3}\%$
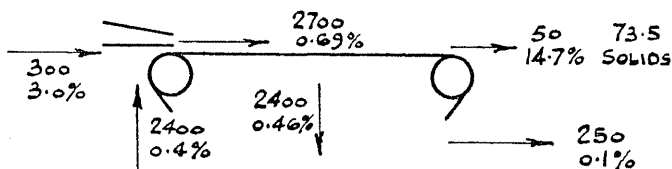
Fig. 1.5b. Conditions after second pass round backwater circuit
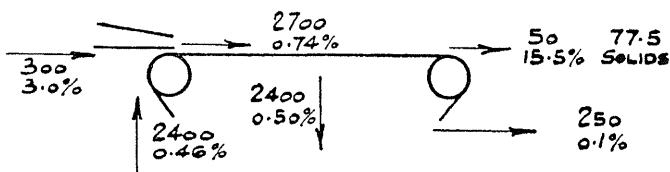
Fig. 1.5c. Conditions after third pass round backwater circuit
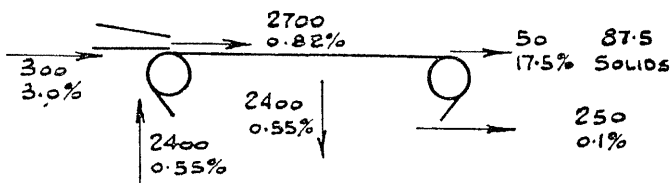
Fig. 1.5d. Final equilibrium conditions with new retention

length of time for correction which increased with the volume of the back-water system and decreased with the flow of backwater used for mixing. In practice retention changes would normally be fairly gradual so the ultimate effect on the weight may, after all, be negligible. This depends entirely on the relative time scales involved.

It is also clear from this example that the retention on the wire closely governs the consistency of the backwater system. The system is self-stabilising and accounts for the fact that the backwater and breast box stock can alter appreciably in character while the same substance of paper is being made; in fact, both backwater and breast box consistency adjust themselves continually to the changing retention conditions on the wire. This is one reason, incidentally, why attempts to relate breast box stock

18

properties, such as consistency, loading content or freeness, to the paper quality are invariably unsuccessful. For instance, Bienkiewicz and Hendry, *et al.* (2, 3, 4) reported tests showing that wetness of fresh stuff on a machine making tissue was 25 deg. S.R. while in the breast box it was 65 deg. S.R.; incidentally the wetness at the couch had returned to 25 deg. S.R. These authors found large variations in breast box consistency and wetness tests with no apparent alteration in fresh stuff or operating conditions and emphasised that breast box tests could not be used for control purposes though readings of this nature can be very useful for detecting and assessing changes in the retention conditions on the wire. It is worth noting in this respect that to a close approximation the consistency of the breast box stock and the backwater keep closely in step, i.e. the difference between the two consistencies remains approximately the same as the retention alters; hence a measure of either consistency would, for day-to-day running, be all that is necessary to assess retention changes on the wire. Retention is affected in practice by numerous factors, and in particular by the breast box consistency itself, so there will be some interaction between these two variables; the factors affecting retention will receive fuller treatment in 1B.1.

Other changes occurring in the backwater circuit will have a similar transient effect on the dry weight. For instance it is common practice for the reject flow from pressure-screens to be passed to a secondary screen from where the accepted stock goes into the main wire pit; in a similar way the accepted stock from the second stage of a battery of cyclones might also be taken to the main wire pit. If for one reason or another either flow to the main pit changes in character, this in turn could affect the backwater and the weight of the paper until equilibrium conditions were re-established. For example, a drop in consistency (with consequent rise in breast box consistency) would have the same type of effect as an increase in retention on the wire; the weight would rise temporarily but would finally return to its original position when the backwater consistency had stabilised at its new, slightly lower value.

It is important to note in the example just given the assumption that there is no change in fibre content of the excess backwater. If this were not the case, in addition to the transient weight change observed (which would still be substantially the same) the final equilibrium conditions would also be altered. Suppose, for example, that excess backwater consistency rose to 0·15 per cent., then the weight of paper would be 86·25 lb. per minute in final equilibrium conditions instead of the original 87·5, in other words the substance is lower and there has been a permanent weight change. To avoid *permanent* as opposed to *transient* weight changes it is desirable to make the excess backwater consistency as low as possible. Hence the superiority of arranging for excess backwater to be primarily from suction boxes rather than a mixture of tray and suction box water from a single silo, a point discussed further in 1A.2 4.

The most important change in the backwater system that occurs in practice is the deliberate one when the machineman adjusts the backwater flow to suit the conditions on the wire, in particular the position of the dry-line. This will frequently be occasioned in the first place by a change

BREAST BOX 3300

FRESH STUFF —————→   0.54%   PAPER 50   96·0
                                          19·2% SOLIDS
300
3·0%   3000 BACKWATER
                       0·27%
BACKWATER 3000   EXCESS BACKWATER
          0·3%   250
                                           0·1%
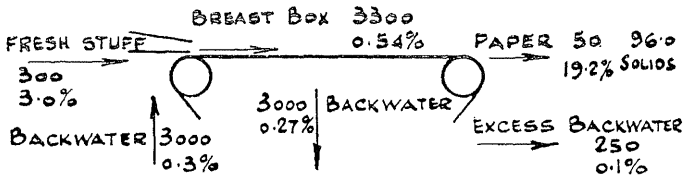
Fig. 1.6a. Flow of backwater in Fig. 1.4 suddenly increased to 3,000 gals. p.m.
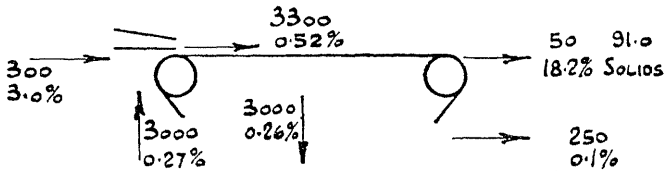
3300
0·52%   50   91·0
300   18·2% SOLIDS
3·0%
       3000 3000
       0·27% 0·26%   250
                                             0·1%

Fig. 1.6b. Conditions after second pass round backwater circuit.

3300
0·51%   50   89·0
300   17·8% SOLIDS
3·0%
       3000 3000
       0·26% 0·255%   250
                                             0·1%

Fig. 1.6c. Conditions after third pass round backwater circuit

3300
0·50%   50   87·5
300   17·5% SOLIDS
3·0%
       3000 3000
       0·25% 0·25%   250
                                             0·1%
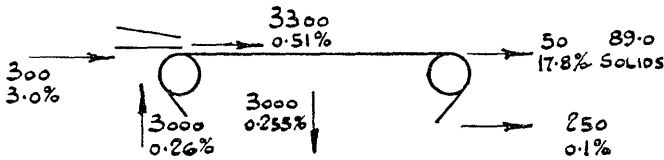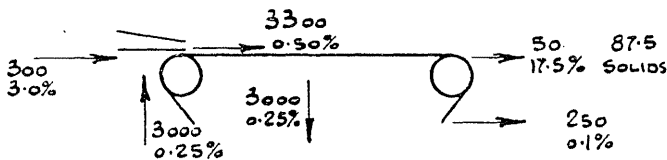
Fig. 1.6d. Final equilibrium conditions with new backwater flow

in retention conditions on the wire but ignoring this point for the moment, the result simply of changing the volume of backwater in circulation is worth studying in more detail.

1A.2 3 Alteration in backwater flow

Using the flow system in Fig. 1.4 once again, suppose this time that the backwater flow is altered from 2,400 to 3,000 gallons per minute. Fig. 1.6a shows the situation at the first pass, Figs. 1.6b and 1.6c at the second and third passes respectively, and Fig. 1.6d the final equilibrium conditions.

In this case the consistencies of the backwater and breast box stock have decreased stepwise exponentially to their final equilibrium values which are 0·25 per cent. instead of 0·3 per cent. for the backwater and 0·5 per cent. instead of 0·6 per cent. for the breast box stock. The weight of the paper

has risen initially to the equivalent of 96·0 solids, dropping with each subsequent pass until the original weight is again reached.

These changes are seen to be the inverse to those occurring when retention decreased. It is interesting to note that decreased retention would in practice lead to the dry line coming back on the wire (because the drainage through the wire would invariably be faster) and this would lead the machineman to add more backwater in the mixing box or pump. Hence, provided the corrective action were performed quickly enough, the tendency for the weight of the paper to reduce transiently when the retention dropped would be offset by the machineman increasing the backwater flow, thereby producing a compensatory transient increase in weight.

It is worth drawing attention to one point of practical importance. When no continuous measure of substance is available, alteration of the backwater flow near the top of a roll should be avoided otherwise the weight reading will be unrepresentative. Most machinemen are aware that altering the backwater dilution flow affects the substance temporarily but the intuitive idea of what happens is misleading. Since increasing the flow of backwater means a reduction in the consistency of the breast box this commonly leads to the notion that the substance of the paper will be temporarily reduced; in fact, as seen above, the opposite effect occurs.

It is apparent from these examples that a change in the consistency of the breast box stock and the backwater follows necessarily from a change in retention or an alteration to the volume of backwater used for mixing. Under equilibrium conditions these variables can easily be shown to be related, and Figs. 1.7a and 1.7b depict characteristic curves of the relationship for different retentions between the volume flow at the slice and, respectively, the consistency in the breast box and in the backwater. If the normal running condition of Fig. 1.4 is at position A, a drop in retention with the same backwater flow as in Figs. 1.5 would lead to a new equilibrium at position B. Similarly a change in the volume of backwater flow at the same retention, as in Figs. 1.6, would lead to position C.

1A.2 4 Stability of the paper machine flow system

In the two previous sections attention has been given to changes that can occur in the substance of the paper when retention on the wire alters or when the backwater mixing flow is altered, usually to take care of a change in retention or drainage rate. These changes will evidently affect not only the dry weight but also, because they involve a selective drainage particularly of short fibres and loading, the characteristics of the finished sheet of paper. To minimize these disturbances it is not sufficient simply to control the flow and consistency of the fresh stuff, the drainage characteristics of the fresh stuff must also be closely controlled. This is primarily a matter for careful stock preparation, which is not the topic under present discussion, but it is also dependent on the whitewater and the broke system since the addition of both whitewater and broke earlier in the preparation plant has an important influence on the fresh stuff drainage.
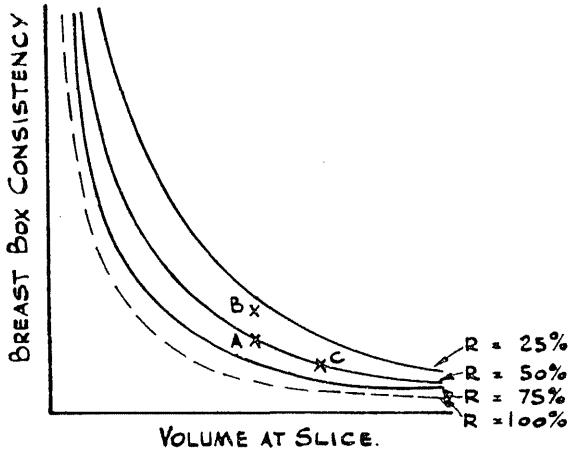
Fig. 1.7a. Relation between breast-box consistency and volume of backwater flow for different retentions (R) on the wire
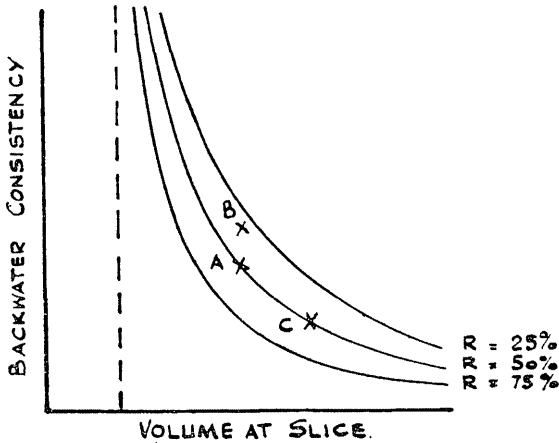
Fig. 1.7b. Relation between backwater consistency and volume of backwater flow for different retentions (R) on the wire

It is not proposed here to enter into any lengthy discussion of the pros and cons of different systems for dealing with whitewater and broke. These depend to a large extent on the type of paper manufactured and on whether the machine makes a variety of papers during a short space of time. The author intends only to state three broad principles which seem desirable if stability is to be achieved.

Firstly, it is important that the excess backwater flow entering the whitewater system is as steady as possible. Any variation in flow rate

22

implies unsteady addition of fresh stuff or, possibly, whitewater or fresh water, and this should be corrected at source. Any variation in consistency means that alterations to the dry weight of the paper of a permanent nature are occurring (as opposed to the transient effects which were considered above). Stability in consistency of the excess backwater flow is therefore important and is usually achieved to some extent by ensuring that the flow is composed of suction box and suction couch backwater since these are lower in consistency and less variable than table roll backwater. This can be arranged by allowing the main pit to collect all the backwater from the table rolls and suction boxes but designing the pit so that the latter overflows preferentially. The danger here is, of course, that the success with which this is achieved is not readily assessed. A preferable alternative is to control the level of the main pit by addition of the required quantity of suction box water, probably with just a small overflow to remove scum and froth that may be suspended on the surface.

The consistency of fresh stuff entering the backwater circuit is generally of the order of 3 per cent. On the wire, drainage usually reduces the con-sistency of the web to this value sometime after the first or second suction box. Thus, although in most systems a small quantity of whitewater or fresh water is also added to the backwater circuit in addition to the fresh stuff, normally the backwater drained from the table rolls will not be sufficient by itself to dilute the fresh stuff in the backwater circuit. The consistency of backwater from the first suction box is generally higher than in the other boxes (see, for example, Bennett (10)), especially the 'dry' ones nearer the couch; as the flow from the first box is equal to that from the last few table rolls, and can be almost as much as from all the other suction boxes put together, this flow alone should often be more than sufficient to make up the deficiency in the main pit. In this event it would be preferable to arrange the backwater make-up to be selected in this way and so take advantage of the higher consistency of the first suction box backwater; it would in any case seem worthwhile to ensure that the main pit deficiency is made up preferentially by flow from this source.

A second requirement for achieving stability is that any fluctuations that do occur in the backwater excess flow should have their influence in other parts of the system minimized. It would be helpful in this respect if the disturbances were confined, so far as possible, at least to the wire circuit. On many machines excess flow composed of suction box backwater is used directly on some wire sprays, on screening and cleaning equipment (par-ticularly, cyclone installations and secondary tremor screens) or in the breast box, and also for sealing the suction box and suction couch pumps. In such applications as these, for any variation in the consistency of the excess backwater flow it should not require long before new equilibrium conditions are established in the wire circuit. On many machines with a closed system, however, it is also the practice to use excess backwater directly for dilution in consistency regulators, beaters, hydrapulpers, etc., in the stock preparation system. This use, though convenient, does carry with it the danger of extending disturbances in the wire section throughout the whole preparation system and will considerably increase the time

23

needed to establish a new equilibrium. It is therefore preferable to take all the excess backwater flow not used directly at the wet-end of the machine straight to some form of save-all, clarifier or thickener. The thick stock from this could then be treated as broke and returned to the system at a suitable point (preferably at a steady rate to reduce the possibility of affecting retention on the wire, since it will be composed largely of fine fibres and loading); the clarified whitewater, at a very low consistency, should then hardly alter in character or consistency and using it for dilution would cause little or no disturbance to be transmitted to the stock preparation system. In some modern systems this is elaborated by having two save-alls or clarifiers in series; whitewater from the first simple clarifier is used for dilution in the preparation and broke system, thinner whitewater from the second clarifier is used for wire showers and suction roll lubricating water. Alternatively a disc filter provides cloudy water for the first purpose and clear for the second. When clear water is used in wire sprays and collected in the machine pit, the tray water from under the wire going to a separate silo, then this spray water should return direct to the disc filter to avoid disturbances in the backwater excess flow.

It may be noted in passing that in completely closed systems, since the water in the web at the couch (70 per cent. to 90 per cent. moisture content) is always more than the water added in the furnish, a quantity of water is required for make-up; in practice it is generally the case that more than this quantity is added in fresh-water sprays at the wire and couch, pump seals, cutting jets, etc., producing some excess. Part of this may be cleaner reject flow and the remainder would be taken to waste from the clarified whitewater chest, which should have sufficient capacity to act as an adequate reservoir for sudden demands on the machine.

The third principle desirable for stability is to keep the excess backwater and the broke system completely separate; wet broke in the form of trim off the wire, or the whole width of web from the wire or presses during a break, should be diluted with clarified whitewater at the lowest consistency available. The reason for this separation is twofold; firstly, it is not desirable to allow any broke to mix with the whitewater system since variation in the quantity of broke added, whether before or after clarification, will affect equilibrium conditions in the stock preparation and eventually in the wire circuit; secondly, if whitewater containing little fines or loading is used for dilution of wet broke then the character of the resulting mixture will be as close as possible to that of the fresh stuff and when added in the preparation system at any point (and it is becoming increasingly common for this to be the machine chest) it should have an indistinguishable effect on drainage characteristics compared to the fresh stuff flow to the machine. Even when, as is obviously desirable, the wet broke is consistency controlled and carefully metered from a storage chest, occasions are bound to arise when there is a considerable excess of broke and it becomes necessary to increase the flow; at such times this use of clarified whitewater for dilution will be most beneficial in reducing the possibility of a vicious circle of broke and breaks arising on the machine.

One difficulty of realizing this in practice is that usually it becomes

necessary to have a separate broke thickening system and whitewater tank. This is because it is not easy to arrange a compromise between having sufficient force of whitewater available during a break at the couch or presses for adequately breaking up the wet web, and at the same time preventing excessive dilution below the 3 per cent. or so suitable if the wet broke is to be returned direct to the preparation system. With machines having an open draw the necessity for a shower on all the time to wash off the sheet at a break makes it impossible to prevent excessive dilution of the broke. However, on pick-up machines powerful high pressure deluge sprays which only come into operation across the width of the machine during a break are meeting with some success in this respect though an added difficulty can be encountered in pumping broke at this relatively high consistency for any distance. With the machine working normally the small amount of trim can be washed off the wire edges and fed to a separate small thickener.

Dry broke creates a rather different problem. Due to the fact that it needs some refining or defibrating before it is suitable for return to the system this necessarily alters its character somewhat from wet broke; it would appear preferable for dry broke to be stored, consistency regulated and metered into the preparation system separately. The manner in which this is accomplished need not differ in principle from that described for the wet broke system. For certain types of paper, particularly wet-strengthened and coated, such a procedure is imperative anyway.

With growing recognition of the difficulties that can occur at the wet-end of a paper machine due to unsuspected disturbances in the whitewater and broke systems, it seems increasingly likely that something along the line of the principles detailed above will eventually come to be regarded as necessary. Certainly machines laid down in recent years have, in different ways, shown much more care and forethought in the arrangement of their systems than is apparent on many older machines.

1A.2 5 Degree of closure of whitewater systems

So far all that has been said applies primarily to completely closed back-water and whitewater systems. On many machines it is common practice deliberately to add fresh water somewhere in the system. The economic advantages of reducing fibre loss have long since closed up the backwater fresh stuff dilution circuit completely except for a very few specialized machines where some fresh water addition in the main backwater pit is still necessary for a specific purpose. The degree of closure of the back-water and whitewater system is usually defined as the difference from 100 per cent. of the percentage ratio between the whitewater flow to drain and the flow through the slice; where all excess flow from the suction boxes goes to drain the degree of closure would be low by modern terms, between 60 per cent. and 80 per cent. Sometimes the excess suction box backwater is taken to a clarifier and only the thickened stock retained; this reduces fibre loss but may still be regarded as a relatively open white-water system since fresh water make-up will be necessary. Such a system

will generally be used on a machine requiring frequent colour changes where a more comprehensive whitewater system with dilution in stock preparation would never have a chance to reach equilibrium and in the short duration of a normal run would succeed only in disturbing the colour balance. A system slightly more closed will involve use of clarified whitewater for sprays on the machine and, perhaps, in a consistency regulator close to the machine. A completely 100 per cent. closed system with no whitewater overflow to drain can only be found where fresh water usage in the system is sufficiently low for some make-up to be needed; this is more likely when using a dry furnish (e.g. 10 per cent. moist bales) or in a hot system when there will be more evaporation of water (though the quantity of water involved in this is not likely to be of much practical significance compared to other losses). For rag and esparto mills and integrated wood pulp and paper mills the paper machine whitewater system can not be considered separate from the pulp preparation system; in the case of the integrated type of mill conservation of fibre and heat makes it most important that the high whitewater surplus on the paper machine is made available in grinders and other parts of the pulp preparation system.

The effect of closing up a backwater and whitewater system has been studied at length by Bienkiewicz, Mardon *et al.* (2, 3, 5). The advantages in economy of fibre and loading and lower heat losses are apparent but closure leads to a progressive buildup in the amount of fibre debris and loading particles in the system. Also the reduced flow to drain, though beneficial for mills with an effluent problem, leads to a greater proportion of fine fibres in the paper once equilibrium conditions are established (more of the fine fibres in the furnish are retained in the sheet) and this alters the characteristics of the paper. In some cases this can be very undesirable; for example it is reported that with glassine opacity is increased. Closing the system has other results which can be very detrimental to efficient running of the machine. The quantity of dispersed pitch and slime in the system grows and foam can become increasingly troublesome. With constant addition of alum, adsorption of alumina on fibres leaves more free sulphate ions circulating in the backwater and the sulphuric acid in the system steadily rises. The pH falls due to this and less alum would be used to keep it steady; this makes the system increasingly unstable to any variation in fresh water addition and changes the chemical conditions affecting retention of loading, dyes, size and wet-strengthening resins. These factors make it necessary in many systems to have a sizable fresh water addition and this should always be as far from the wire backwater circuit as possible to reduce disturbing effects; certainly in normal cases fresh water should never be added in the backwater pit and usually the whitewater tank is the obvious place. Build-up of fine fibres and loading in the backwater as the system is closed will also reduce retention on the wire leading to an increased breast box consistency. Occasionally this may be so excessive (e.g. with groundwood furnishes) as to impair the ability of the machineman to form the sheet with the quantity of water he is able to drain from the wire. In this event it could become necessary to open up the system.

Another factor which is closely related to the degree of closure of the backwater and whitewater system is the time required for equilibrium to be reached throughout the system. Hendry (4) has reported that the backwater loading consistency of a tissue machine with a highly closed system required five or six days to reach equilibrium, and when making coloured paper the hue of the backwater continually changed due to the fine fibres which accumulated being preferentially dyed by one or other constituent. If backwater or breast box consistencies are tested at regular intervals from start-up it will frequently be found, particularly with machines making papers carrying a high proportion of fines and loading, that the consistencies steadily rise throughout a period of days. This is directly due to the reduction in retention occurring with the increasing proportion of fines and loading in the backwater circuit.

Calculations by the authors quoted above showed that equilibrium conditions from start-up are established in an exponential manner (similar to the examples illustrating the effect of changing retention and backwater flow given earlier). If a proportion of fresh water is used in place of backwater for dilution in the mixing pump or box then the final equilibrium conditions are altered and, as expected, the greater the proportion of fresh water added the lower the equilibrium consistencies in the backwater circuit. Addition of a small quantity of fresh water in this way to a completely closed system has a greater effect on the equilibrium consistencies than subsequent additions. At start-up, the backwater consistency will rise to within approximately 5 per cent. of final equilibrium after three passes and within 1 per cent. after five passes round the circuit (allowing for the fact that the retention will be lower at first when the breast box consistency is lower); thus if the capacity of the main pit, piping, cleaners and breast box is, for example, equivalent to four minutes of flow through the slice, then the substance of the paper should be within 5 per cent. about 12 minutes after the fresh stuff valve is open and within 1 per cent. after about 20 minutes. Subsequent changes in the backwater circuit and establishment of final equilibrium will depend, of course, on the design of the whitewater system and on many machines true equilibrium may never be reached within normal working runs.

1A.2 6 Formation and wire conditions

Though only indirectly connected with the wet-end flow system one topic is conveniently considered in the present section under the heading of theory—that of the relationship between the slice jet velocity and opening and the wire speed. The formation of the sheet of paper on the wire is closely determined by the relative speed of the wire and the jet from the slice at the point of impingement. This relationship (usually termed the efflux ratio) will be discussed in greater detail elsewhere and for the moment it is only necessary to stress that under given conditions for each wire velocity there must be, within fairly close limits, a slice jet velocity which is most suitable to get the best formation. Normally these two velocities are very close though for some types of machine with an upsloping

wire and for certain papers requiring a special fibre orientation (e.g. twisting paper) the velocities can be quite different.

The jet velocity is directly controlled by the pressure head behind the slice and this in turn is governed by the level in the breast box (due account being taken of air pressure difference in air-loaded boxes). If the coefficient of discharge of the slice is known it is possible, as shown in 1A.1 5, to calculate the head appropriate for any slice jet velocity; however, any loss in head due to friction at the slice walls and also across breast box fittings in front of the slice, such as perforated rolls or evener plates, will affect the calculation. Pressure loss across a perforated roll is smaller than across evener plates, Attwood and Alderson (49) found it to be approximately 0·4 in. compared to 2 in. for a 45 in. head, but the loss will alter with position in the breast box and also with the velocity of flow. In theory, then, the head at the slice can be related to the wire speed by a general formula which takes the form

$$h = \frac{3}{16} \left[\frac{V}{60C} (1 - p/100) \right]^2 + \delta q$$

where h is the head in inches, V the wire velocity in ft. per min., C the coefficient of discharge, $p =$ the optimum percentage by which the jet speed should be slower than the wire speed for the best formation, and δq is equivalent head loss in inches across breast box fittings in the slice. In practice, neither C nor δq are known to any degree of accuracy (according to Beveridge and Bridge (80) C is not even constant on any particular machine but varies significantly with changes in stock consistency and other characteristics). Also p can only in the first instance be guessed at, so it is really only feasible to use this relationship as a guide. For that purpose when C is close to unity, as in a projection slice, the simplified formula usually quoted in one form or another, $h = V^2/19,200$, is probably adequate. The head appropriate to different wire speeds (or speeds measured elsewhere along the machine if allowance is made for the normal difference due to draw), as calculated from either of these formulae, may be presented in a suitable form to the machineman who then has a useful basis from which to learn, by experience and by experiment, the difference between the calculated and running heads which usually gives the best results under any particular conditions. Alternatively, the calculated jet velocity for the head measured at the slice can be compared with the actual velocity of the wire. This has the advantage of providing a linear scale, whereas differences between heads increase with the square of the velocity; thus it is then easier to compare the normal percentage velocity difference or the efflux ratio at different speeds.

While the wire speed determines the pressure head required behind the slice, the quantity of backwater used for diluting the fresh stuff determines the width of opening in the slice. This is evident because if the velocity of the slice jet is fixed the volume can only be varied by adjusting the slice opening. Thus, strictly speaking, whenever the machineman requires an alteration in the volume of backwater in circulation in the wire circuit this should be accomplished by moving the slice up or down. If the level

in the breast box is not automatically controlled then a further adjustment becomes necessary to bring the level back to its original value, thereby leaving the pressure head at the slice unaltered (at least within practical limits). In practice it is common for alteration of the slice lip to be avoided as much as possible because of the difficulties which may be encountered with cross-level changes (see 1B.6 3); consequently the quantity of back-water in circulation is only altered effectively by changing the level in the breast box, i.e., the velocity of the jet. While such a procedure may be a reasonable compromise for very small changes it is very important that the machineman realizes that by this action he is not only altering the amount of 'water on the wire,' he is also affecting the formation to some degree. The obvious danger is that the two effects become confused and the formation alters to such an extent that it affects the drainage charac-teristics which the machineman is trying to correct. A vicious circle may well be set up until the whole wet-end is in a completely chaotic state. Sometimes the only way of avoiding this is to put limits to the extent by which the machineman is permitted to adjust the slice pressure head so that under unusual conditions he reaches a point when the slice opening has to be altered and any adverse cross-level effects from this have to be faced up to and corrected. Occasionally drainage on the wire is so limited, and the slice flow so low, that the slice opening would be too narrow for a satisfactory sheet to be made without every small irregularity in the slice lips appearing in the paper; under such conditions formation would be sacrificed to obtain a satisfactory cross-level by opening up the slice, allowing the head to drop. It would then be especially valuable to set a limit on the difference tolerated between the required and running head or velocity to prevent formation and other paper qualities deteriorating too much.

When making an alteration in machine speed to suit general running conditions the machineman will make a corresponding change in the fresh stuff to keep the substance the same and will also alter the breast box level (and hence the flow through the slice) to keep the correct relation between the slice jet velocity and the new wire speed. Provided the slice opening is not altered then, for all practical significance, the effect of these alterations is simply to reduce all the flow velocities round the backwater circuit proportionately. The consistency of the breast box and backwater is unaltered, which is precisely the condition required.

When altering the machine speed to effect a relatively small substance change for the same grade of paper the position is different. In this case a familiar situation is one in which the speed is altered by an amount which is roughly inversely proportional to the substance change; the gross production at the reel-up is then unchanged, as is the quantity of water drained at the wire and presses, and evaporated in the drying section. By this means the machine is kept running at what is presumably an optimum speed to suit the drainage and steam capacity available. For this type of change when the fresh stuff flow remains effectively untouched it is necessary, in order to keep the same flows and consistencies in the backwater circuit at the new speed, that in addition to altering the head

at the slice, the slice opening must also be adjusted proportionately to the velocity change. In fact if the main flow valve feeding the breast box is left untouched while the slice is opened sufficiently to obtain the new head required, then the desired condition is reached.

For larger changes of substance other factors, in particular altered retention characteristics on the wire, affect the validity of the foregoing. These aspects are intimately tied to the particular machine and paper concerned

Breast box flow of 2430 reduced from 2700 by 10% drop in slice jet velocity.
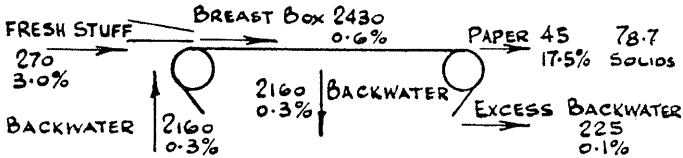
Fig. 1.8a. Conditions in Fig. 1.4 altered to take care of a machine speed reduction of 10% with same substance paper, i.e. solids flow at couch also reduced by 10%. Slice opening unchanged

Breast box flow of 2700 unchanged: 10% drop in slice jet velocity balanced by approximately 10% increase in slice opening.
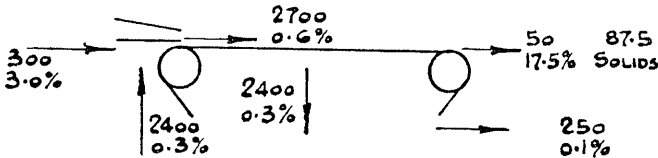
Fig. 1.8b. Conditions altered to take care of substance increase of 10% and corresponding speed decrease of 10%, i.e. solids flow at couch unchanged. Slice opening increased by 10%

and are not discussed further. For clarification of the two points raised in the preceding paragraphs, the wet-end conditions used for illustration in Fig. 1.4 are shown in Figs. 1.8a and 1.8b as they would be at 10 per cent. reduced speed, without and with an accompanying substance change.

OPERATING FACTORS AFFECTING PERFORMANCE OF THE WET-END FLOW SYSTEM

1B.1 RETENTION ON THE WIRE

The importance of maintaining steady retention conditions on the wire has been considered in some detail from a theoretical standpoint. It is appropriate now to set down the various factors which affect retention in order to assess what parts of the wet-end it is desirable to control. Some of these factors affect not only retention but also the general drainage conditions on the wire, in fact of course the two are closely connected. Drainage and its effect on formation will form a later subject for discussion but it is emphasized that factors which affect retention can disturb not only the substance and fines retained in the paper but also the whole formation, and the effect on the latter can be quite as important for maintaining satisfactory paper quality.

1B.1 1 Composition of the furnish and the effect of beating

The constituents of the furnish and the treatment given to it in the preparation plant set the whole character of the wet-end flow system. Retention on the wire is closely affected by the degree of beating or refining since development of fibrillation and the increased proportion of fibre debris changes both the composition of the stock and the matting conditions on the wire. Retention will also be affected by the proportions of short to longer fibre pulps mixed in the furnish and by the addition particularly of loadings and dry broke. It is not possible to make any useful generalizations about the effect of composition of the furnish on retention, so much depends on the particular circumstances. In all mills, however, an attempt is made to keep the composition of the furnish steady so that the quality of the paper remains uniform, and this will also necessarily help to keep retention conditions steady.

It is almost universal practice to use the results of freeness or wetness tests to assess the degree of beating or refining given to individual pulps. In fact, an appreciable amount of research is directed at the present time towards developing a satisfactory continuous freeness instrument with which it is hoped to control refiners and in some cases this is already being attempted (57, 63, 64, 75, 93). This procedure seems to the author to be satisfactory only in so far as the freeness test, duly corrected for consistency and temperature variation, is an adequate measure of the beaten condition of any particular pulp and correlates with development of the final properties of the paper made from it. Originally the test was designed to predict how a furnish would drain on the wire and subsequent work showed that

in the case of individual types of pulp the results obtained from the test are closely related to the duration of beating. But in many circumstances, especially where large quantities of fines are involved, the test can give spurious results. The main concern when using any beating equipment must be to control the manner and degree of beating to that found to be most suitable for the paper to be made, and in some circumstances other measurements, for example refiner load or temperature rise, may well be better than freeness for this purpose.

While the use of the freeness test for control in beating of individual pulps may prove very useful in ensuring uniformity of treatment, freeness results for the final furnish going to the machine must be used with far greater care. They seem in this case to have two purposes: to act as a control on the total beaten condition of the furnish, as for individual pulps, and to predict and keep steady the drainage condition on the wire. If their use is primarily to control the beaten condition of the fresh stuff then the same restrictions apply as for the practice of taking the tests on individual pulps; in this case, however, because the proportions of different pulps, dry and wet broke, whitewater fines, etc. will alter from time to time, it is much less likely that freeness figures on the final furnish will bear any but a very rough relation to development of the paper properties and so their use to control beating of one or other constituents of the furnish earlier in the stock preparation system must be carefully justified. It is interesting in this respect that Mardon *et al.* (5) quote that the power used in refining a tissue stock was reduced from 670 to 460 k.w.h. per ton within 24 hours from start-up to keep the wetness constant at 480 deg. S.R.; this illustrates well the effect of fines building up in the whitewater and altering the apparent wetness. Also for the same machine Hendry *et al.* (4) found that addition of backwater fines to refined stock had the effect of making it appear slower, from 23 deg. S.R. to 33 deg. S.R. for 10 per cent. addition and to 50 deg. S.R. for 20 per cent. addition by weight. The effect also depended to a slight degree on whether the backwater originated from a tray collecting the breast roll and the discharge from some dandy-type table rolls or from a second tray draining some solid table rolls, which shows how easily the freeness test on a composite furnish can be influenced.

On the other hand, if the use of freeness tests on the machine furnish is primarily to give a guide to forthcoming drainage conditions on the wire, then their value is also not very likely to be great. This is due to several well-known limitations of the freeness and wetness testers as a means of simulating drainage (consistency, suction and other factors differ from those on the wire), and also because drainage on the wire is dependent as much on the backwater condition as on fresh stuff (see **1B.1 2**). Thus, freeness tests on the machine furnish can usually at best serve only to indicate the uniformity with which the whole system is functioning and a rise or fall in test figures could be caused by a variety of factors other than beating and refining. The danger of a continuous freeness tester on machine furnish or in measuring and reporting freeness figures on a routine basis is that the results come to be used as a criterion for the degree of treatment the furnish has received and any difficulties at the wet-end of

the machine may too readily be traced to a variation in the freeness figures; in time the refiners may come to be run more to suit the wire conditions of the machine than the properties of the paper manufactured while the compromise needed should, of course, be much more the other way.

A further use of the freeness test has been reported by Tousignant and Madgett (79), who installed a continuous freeness tester on the breast box stock of a newsprint machine as a means of assessing stability of the system. Variations in the freeness record obtained in this way were found to have a connection with draw at the couch (presumably due mainly to changes in moisture content of the sheet at the couch resulting from different rates of drainage on the wire). General fluctuations in the freeness record were compared with various records obtained in the stock preparation and blending process in an endeavour to detect the sources of disturbance, and alteration to the whitewater dilution consistency, broke addition flow rate, proportion of sulphite pulp to groundwood in the furnish, and other aspects of the system were made in order to try to reduce variations in the freeness record. The main problem in using this sort of approach is that, although fluctuations in drainage rate on the wire originate at least in part due to differences in the composition of the machine furnish, these are likely to be detected much easier by direct assessment of the furnish itself, rather than by taking the flow box stock which is dependent also on various conditions on the wire and is in any case part of a self-stabilizing system. Further, for the intention of providing a means of assessing stability, a more satisfactory (and simpler) approach would be to measure flow from one or more table rolls; this has the additional merit of giving a direct measure of drainage rate variability on the wire, rather than relying on a complicated simulation device.

Returning to discussion of the effects of the furnish on retention conditions on the wire, it is evident that the greater the proportion of fibre debris and loading in the furnish the lower will be the retention. Fines and loading, particularly the latter, predominate in the backwater and can virtually control the drainage conditions on the wire. For instance the following results are typical for one newsprint machine (fibre fractionation figures obtained in a Bauer Mc.Nett Classifier and corrected for ash content):—

	Consistency %	Ash on solids %	Long fibres >48 mesh	Short fibres <100 mesh
Fresh stuff	3·0	8	43	42
Breast box stock..	0·6	22	24	67
Backwater (main pit) ..	0·3	40	trace	97
Whitewater (suction box)	0·11	57	trace	97

It is important to note particularly the high loading content (china clay) in the backwater and even higher percentage in the whitewater. The retention of loading on the wire is under 10 per cent. whereas the overall retention is 55 per cent.; even fine fibres less than 200 mesh have a retention of about 40 per cent. Similar very low retentions for loadings (11 per cent.–13

per cent. for diatomaceous earth, 4 per cent. to 6 per cent. for talc and china clay) have been reported by Hendry (4), while results given by Bennett (10) for a newsprint machine also show a clay retention of only about 10 per cent. Under these conditions it is apparent that only a slight alteration in the drainage conditions could have a large effect on the loading circulating in the backwater which, as with consistency variations, would have a substantial (though transient) effect on the quantity of loading retained in the paper until new equilibrium conditions were established.

1B.1 2 Drainage conditions on the wire

The retention conditions on the wire, apart from being governed by the composition of the machine furnish as discussed above, are affected by other factors which alter the character of drainage on the wire. The most important under this heading are the consistency of the slice stock, the substance of paper (i.e. thickness of the fibre mat on the wire), machine speed, temperature, wire mesh, and aeration of the stock. Each of these will be discussed briefly.

The interaction between consistency of stock in the breast box and retention on the wire has already been mentioned in some detail; apart from the consistency being essentially governed by the retention it is generally considered that, other things being equal, a lower breast box consistency will reduce retention. It is difficult, however, to isolate effects on retention caused solely by the breast box consistency because other conditions, in particular the speed of the machine and substance of the paper, are likely to be altered at the same time. In practice the normal running variations in consistency probably have only a small effect on retention; Bennett (10) reported that in a series of trials on a newsprint machine breast box consistency did not have a significant effect on general drainage conditions, though Hendry (4) on a tissue machine obtained a significance relation such that retention decreased with reduced consistency. These workers are in agreement, however, as to the effect of wire speed, an increase of which reduces retention; this has also been reported for retention of loading by Hansen (1), working on an experimental machine, though the determination of the results and manner in which the backwater system was operated in this work are not clear from the article. Hansen also reported an increased loading retention at a higher substance and this was confirmed for overall retention conditions by Hendry.

The direct effect of temperature of the breast box stock on retention was not found to be significant in the work reported by Bennett though it is likely that the increased drainage rate at a higher temperature would normally cause the breast box consistency to be reduced and this could lead to a lower retention. A finer wire mesh obviously improves retention and normally on any machine the mesh used is as small as possible compatible with adequate drainage being possible and a reasonable wire life. In a similar way a wire becoming made up will alter retention conditions. Aeration of the breast box stock reduces the rate of drainage

on the wire and probably affects retention for this reason. However, aeration is considerably more important for its effect on other conditions at the wet-end and will be dealt with separately.

1B.1 3 Chemical conditions

It is becoming increasingly common for chemical additives to be put in at the wet-end of the paper machine rather than in the preparation system, Liquid alum, loading, dyes and wet-strength additives may all be added in the backwater pit or the mixing pump and this procedure has the merit of permitting a closer and quicker control of their effect on the finished paper. Rosin sizing may also be added in this way though it is more usual to add it earlier in the stock preparation system to allow sufficient time and achieve better conditions for precipitation to be more closely controlled.

Retention can be affected by the chemical condition of the backwater; for example, Bennett (10) reported that a lower pH increased retention, while Hendry (4) found that urea-formaldehyde wet-strength resin addition increased retention. Some chemicals such as Sveen glue and activated silica sol are used expressly to improve retention of fibre and loading, though Hansen (1) considered the effect of Sveen glue was confined almost entirely to the loading, and calcium chloride added after refining has also been reported to have this effect (71).

Generally it is more important to control the chemical condition of the backwater, particularly the pH, for reasons other than that of retention. A low pH accentuates the likelihood of corrosion, particularly with an aerated stock; this is because air bubbles in the stock provide carbon dioxide and oxygen which combine with hydrogen ions collected on the metal surface as a result of dissociation of water—removal of these ions allows further hydrogen ions from the metal to form causing further corrosion. Apart from damage to metal, corrosion products may be transferred into the stock solution producing discoloration and black specks in the paper. The pH is also thought to have an effect on flocculation tendencies though there is some doubt about this; on the other hand some deflocculating agents apparently do not function at all with alum present and their addition may even worsen flocculation.

1B.2 FRESH STUFF FLOW AND MIXING

Flow of fresh fibre to the machine must be as steady as possible and this implies constant consistency and constant flow. By suitable choice of pipe size the effect on the total fibre flow of variations in consistency can be minimized (see 1A.1 4) but this can only be regarded as a palliative. Both consistency and flow of fresh stuff require careful control. The manner in which this is achieved depends on the machine set-up and broadly three methods can be distinguised: the old-fashioned mixing box with or without separate consistency regulator, the combined mixing box and

consistency regulator, and the more modern mixing pump with or without stuff box and a separate regulator.

1B.2 1 Consistency regulation

It is not proposed to enter into any detail about the problems and limitations of present methods of consistency regulation. Suffice it to stress that none of the popular instruments available at present regulates consistency: in one way or another all types depend on measuring a form of viscosity of the pulp and any factor which affects viscosity, the proportion of fines, freeness or temperature, affects the working of the regulator even when the true consistency is unaltered. One instrument which actually does measure consistency is of the balanced U-tube type often used for specific gravity measurement of slurries, but the difference in density of fibre and water is so small that the sensitivity of this device has to be very great for it to be useful and problems are likely to occur, particularly with aeration.

Despite the limitations of consistency regulators there has been a tendency in recent years to use more of them in series through the stock preparation plant, on the theory that each will help to smooth out further the irregularities left by the previous regulator. But there is a distinct danger in this procedure, particularly if a regulator is used finally on the mixed stuff feeding the paper machine; the uniformity of consistency from earlier regulators could, in fact, be worsened because of the distorting effects on viscosity caused by differing proportions of broke, loading, etc. In addition, variation in the whitewater consistency and composition used for dilution could have a similar effect on the regulator, and this incidentally is another reason, apart from the question of keeping stable retention conditions on the wire, why it is preferable to use clarified whitewater in the stock preparation system. Consistency regulators can also be be bedevilled by poor mixing and too long a time-lag between the point of dilution and the measurement; generally the best system is one in which the dilution takes place at the inlet side of a pump and the sampling as close as practical to the discharge side. The dilution water pressure upstream of the control valve should be constant to avoid offset in the control point.

It is very important that a check is kept on the performance of a regulator by taking samples at intervals for accurate laboratory determination of consistency. The frequency with which this is done is a matter for individual decision but it is useful to take sufficient to enable a mean figure and a measure of the spread of individual readings to be calculated each week or, on a machine with frequent changes, at least for a typical making which recurs frequently. In this way trends in the average, and any undue variation associated with clogging viscosity tubes, mechanical friction, etc., are readily detected and the instrument can then be rigorously checked when appropriate. In some mills consistency determinations are taken on a routine basis and, for example, Moore and Walsh (66) reported that they use hourly tests to adjust the set point of a De Zurik regulator. Provided

the known accuracy of the test figures is used to set limits within which the control plant is not adjusted (to avoid making alterations for test differences which are not significant), this seems to be a worthwhile though perhaps rather tedious approach; in this particular case, the authors used the consistency regulator signal output to adjust the control point of a magnetic flow meter in the fresh stuff line in an attempt to keep a constant fibre flow to the machine.

1B.2 2 Fresh stuff flow control and mixing

In the older type of mixing box and also in the type incorporating a consistency regulator, the basic control of the flow of fresh stuff and back-water is usually through gate valves; the pressure behind the gate valves is kept constant by having overflows from levels which may also be adjustable. This design, even when improved by using an orifice instead of a gate valve to introduce the stuff, suffers from the relative coarseness of the adjustments and the fact that the volume flow is dependent on the head behind the valve (which will vary despite the overflow), and on the consistency and other flow characteristics including viscosity. Further, mixing is often achieved by cascading fresh stuff and backwater through valves sited opposite one another in a compartment and this must induce considerable aeration. With the type of mixing box which includes a consistency regulator it is sometimes the practice to adjust the set-point of the regulator to produce small changes in substance; while certainly practicable it is difficult to determine whether this works better than altering the volume flow, though the method may have advantages when the fresh stuff control valve is crude.

On faster machines it is usual to use a pump for mixing, and fresh stuff flows to the pump from a stuff box giving adequate head. Though it is not always possible, the inlet to the suction side of the pump should be drowned and trumpet shaped to give a smooth flow entry for the backwater. On some machines where the mixing pump is above the backwater pit, a non-return valve may be used at the bottom of the inlet pipe to allow the pump to be primed; this arrangement is not always satisfactory because unless regularly cleaned the valve is a frequent source of trouble from sticking and slime growth, and with age gets stiffer and provides a strong resistance to the flow thereby affecting the suction head. A suction line diverted from the suction box pump can be used to prime the mixing pump very quickly and is generally a more satisfactory solution.

The flow control valve in the stuff line must be capable of sensitive adjustment and located well below the stuff box to prevent the development of pressures below atmospheric on the downstream side. Most stuff valves are of the plate type and are not sufficiently sensitive for making small changes in substance; there is some merit in having a small by-pass flow for this purpose though this often introduces some practical problems. The Egger diaphragm regulating-valve which keeps a circular opening for all positions rather like the iris of a camera has recently been claimed to have some advantages, particularly in giving a consistent performance and in keeping clean (43). There should be a separate cut-off gate valve to allow

the fresh stuff flow to be stopped without altering the position of the control valve.

Opinion differs as to whether the fresh stuff should be introduced directly to the mixing pump inlet by means of a suitably placed pipe entry or to the main pit close to the point where backwater is drawn into the mixing pump suction. The main advantages of the latter arrangement are that priming the pump is easier and there is less possibility of air inclusion when the stuff is turned on. In addition there is probably less risk of poor mixing and stratification with entry to the pit than may occur in a pipe joining in a tee-branch to the suction side of the pump; also if the mixing pump is suddenly stopped the stuff passing down the stuff box before the valve is closed is less likely to cause trouble if it flows to the pit and cannot lodge in the pump suction line.

To keep the flow of stuff steady it is important that the pressure difference between the stuff box and the point of entry to the backwater is constant. With a pipe joining to the suction side of the pump changes in the pump speed or discharge control valve position (for drawing more or less backwater for dilution) will alter slightly the suction at the bottom of the stuff pipe. On some machines speeding up the mixing pump can be seen to produce a drop in the overflow level of the stuff box for this reason. If the stuff pipe enters the main pit close to the suction pipe entry at a point where the flow velocity is reasonably low, and if the level of the pit is adequately controlled, this change in suction will be avoided.

Recently there has been a tendency to abandon the stuff box as a means of feeding fresh stuff to the machine in favour of using a magnetic flow meter to control the flow in a pipe taken directly from the machine chest. The magnetic flow meter, though difficult to calibrate for such large volumes, is more accurate and reliable than a simple orifice or venturi meter, especially at fresh stuff consistencies, and some success has been reported with this instrument (20). The main advantages claimed are avoidance of aeration in the stuff box and elimination of overflow, which reduces power consumption and removes a potential slime collecting line. Also a visual record of the flow and a relatively accurate means of setting the substance is provided. The control point for the substance can, in fact, be cascade-controlled by a signal from a consistency regulator, thereby helping to keep the fibre flow steady irrespective of changes in consistency. The success of the method must depend entirely on the accuracy of the magnetic flow meter and there is not as yet much data available to show how the meter is influenced by aeration, temperature changes and other variables, nor have there been any reports comparing the long-term uniformity of substance at the reel-up when using the meter in place of more conventional methods.

1B.3 BACKWATER AND WHITEWATER SYSTEMS

There are almost as many methods of arranging the backwater circuit and whitewater flows as there are machines. General principles have been discussed earlier and only a few special points will be made here.

1B.3 1 Backwater pit and the flow control valve

Backwater discharging from the table rolls is usually collected in trays and lead to a main pit situated either directly under the wire part or at the side of the machine. Occasionally the backwater may be allowed simply to drop through the return side of the wire into a pit. The primary consideration here is to prevent excessive aeration in collecting the backwater and in this respect the use of trays and carefully designed chutes is really imperative. In the pit itself it is desirable to arrange compartments to channel the flow in a suitable manner. It is difficult to state any general principles but the main aim must be to prevent any dead spots and ensure a smooth and sufficient flow rate to obviate any tendency to settle (1·0 to 1·5 feet per second is one estimate of the velocity required for this). Important also in this respect is the volume of the pit, which should not be too large otherwise apart from the flow being stagnant the time taken to reach equilibrium condition at start-up and after a disturbance will be longer. The pit should slope slightly down towards a point where the drain is situated so that heavy contaminants can settle during running. In level-controlled pits a small overflow is usually desirable to remove accumulated froth.

While the flow of fresh stuff is normally controlled by a valve in the stuff line, the flow of backwater dilution in the enclosed type of system is adjusted by controlling the whole flow usually with a valve situated on the discharge side of the mixing pump. The opening of this flow control valve is determined in the first place by the amount of dilution required for the stock feeding the machine; however, with a particular slice opening the head in the breast box will vary with the flow passing through the valve, so it is usual in more modern installations to control the head from the flow control valve, either manually or automatically. This has lead to the need for a more sensitive valve than the usual butterfly type and in this respect particularly the Egger and Beloit valves are reputed to permit more accurate and consistent setting and to be well suited for automatic control. When the slice head automatically controls the flow control valve it is desirable to have a reset or integral operation incorporated to avoid offset in the valve position. Other control systems are in use, especially where the mixing pump motor is A.C. and it is not possible to reduce the flow as in a D.C. motor; these are dealt with in 1C.1 4.

1B.3 2 Fresh water addition and the whitewater system

On machines where addition of fresh water to the backwater pit is a deliberate policy, it is important to keep this flow closely under control. If this is not done the breast box consistency and temperature will fluctuate and retention may vary with changes in the chemical condition, particularly pH, of the backwater flow, thereby affecting the substance and composition of the paper. On most machines fresh water is only added deliberately in the whitewater tank where its influence will be much smaller but it is still important for the same reasons to control carefully the fresh water actually used on the machine. In a completely closed whitewater system excessive

introduction of fresh water will increase the overflow to drain. In this respect pump seals can admit a surprising quantity of fresh water and should be set and controlled with a rotameter whenever possible. If fresh water sprays are necessary on the wire it is advantageous to collect and drain off this water separately from the rest of the system. Where fresh water sprays are used directly on the stock the temperature of the water should be preferably near that of the stock.

The use of whitewater, clarified or otherwise, for sprays, vacuum pump sealing, etc., on the machine should be measured, even if only at intervals, to prevent the system altering in balance over a period and gradually producing changes which are difficult to detect. In fact, this applies equally well to the whole whitewater balance which should also be checked in much greater detail than it normally is on most machines. On existing machines this task is unfortunately often very difficult though it is always most useful to know the total fresh water consumption in the flow system and also the flows of thick and thin stock to drain. On machines built recently it is commonplace to organize the whitewater system with considerable care and provide flow measuring instruments at these points as well as to measure the individual whitewater flows used in consistency regulators, hydrapulpers, etc. (35, 36, 51, 58, 61).

On some types of whitewater save-all a certain quantity of longer-fibred 'sweetener' stock is required to make a mat for retaining the shorter fibres predominating in the whitewater; in this case the save-all may actually be incorporated in the machine fresh stuff feed system, i.e. the thickened stock immediately becomes part of the fresh stuff flow. There seems to be considerable danger here that variations in whitewater consistency and flow (being mainly fines) will alter the fibre-length balance of the fresh stuff which would then produce instability in retention conditions on the wire. If this type of disturbance is to be adequately avoided, it is preferable to have a separate tank to receive the thickened stock from the save-all, and meter it at a constant rate into the fresh stuff flow or machine chest.

1B.4 BREAST BOX APPROACH SYSTEM

With increasing machine speeds more attention has been devoted to the design of the approach system to the breast box. The old method whereby stock entered through one or more holes at the bottom of the breast box began to prove inadequate mainly because of the difficulty experienced in keeping the substance of the paper level across the web. It was found that permanent velocity differences existed at points across the slice causing some places to be heavier than others, and this can only be corrected within narrow limits without causing undesirable waves on the wire and distortion of the slice. But a more difficult and more common problem than this is the general instability in the uniformity of flow across the machine which a poor approach system can produce, and this can only be alleviated by filling the breast box itself with various devices in an attempt to smooth out the flow. The influence of the approach flow on formation depends primarily on the degree of turbulence and flocculation of the stock on

entering the breast box but this is more important when considering the design of the breast box and slice. As a general principle it may be stated that a moderate amount of turbulence is desirable in the approach system but the most important requirement is to spread the flow as evenly as possible, without leaving persistent cross-machine flows, so that it enters the breast box proper at uniform velocity all across the machine.

1B.4 1 General approach system

The design of the approach piping to the breast box is governed to a large extent by the layout of the machine and the stock cleaners and screens in use immediately before the flow enters the breast box. With open strainers on slow machines the flow is usually collected into a common pipe. On faster machines the flows from several open strainers or from the enclosed type of screen are lead to the breast box in separate pipes. With such a system as this the immediate difficulty is to keep the flow matched in each breast box inlet pipe. Pressure gauges or visual assessment are not really satisfactory for this purpose; inlet velocity differences have been found to persist to the slice and fluctuating cross-flows which react with one another and form vortices at the front wall of the box can occur for the same reason. Also the width of the screening equipment is frequently wider than the machine, which makes even entry from each screen more difficult to design. Because of this the trend on faster machines seems to be towards a return to using the common pipe into which each screen discharges before the approach system proper begins; sometimes the pressure remaining after screening is inadequate for the speed of the machine and a second pump may be used to take stock into the breast box.

The use of the newer enclosed screens has permitted the whole wet-end system to be enclosed and this is generally considered to reduce the risk of aeration while permitting a closer control on the flows in the system. On faster machines these advantages are considerable though aeration can still be a major problem due to the instability of flow that can occur when air is present in stock pipelines. This will be discussed in greater detail in **1B.7**, but it may be noted that it is very important to have all pipe runs in the approach system sloping upwards (at an angle of at least 5 deg. to 10 deg.), with air vents at top points preceding a downward slope if this cannot be avoided. It is also considered profitable to slope bends gradually to prevent the build-up of excessive eddies which may vary in size and cause the main flow to fluctuate in velocity. For really sharp bends a specially designed hydrodynamic shape is desirable. This requirement is particularly necessary close to the breast box but the effect of surges caused by a disturbance anywhere in the system has been shown to persist right through to the slice (see **1B.8**).

1B.4 2 Comparison of different approach systems

The inadequacies of any design for spreading the flow of stock from a single pipe to the full width of the machine prior to entering the breast

box proper are shown up much more at higher speeds where inequalities in flow from the slice are more obvious and troublesome. For this reason most of the work done on this particular problem, as in fact with breast box and slice design also, has been carried out on comparatively fast machines or on models designed to simulate behaviour of fast machines. With slower speed machines the main problem is generally to avoid dead spots in the approach system which could gather slime and froth, while at the same time keeping the stock adequately in suspension and preventing flocculation by using a perforated roll at the point of inlet to the breast box; the flow velocities are generally lower than on faster machines (especially in the breast box), and inequalities in the approach have a greater chance to even out.

Work on approach systems has also generally been associated with investigating the breast box and slice design and it is usually difficult to separate the two. Two principal methods have been used. Firstly, the flows have actually been measured using various specially designed instruments to overcome the lack of sensitivity of the simple pitot tube, but at the same time disturbing the flow as little as possible; from this the variations in velocity and positions of eddies and cross flows have been studied. This technique has been confined more to experiments on model approach systems. Secondly, the pressure of the flow as it leaves the slice has been measured and the variations have been related to the approach flow piping. Investigations reported in the literature have been undertaken mainly by Mardon and his colleagues (12, 17, 24, 40, 53, 77, 89), but reports have also been given by Reitzel (46), Baines *et al.* (22), Nelson (55), and Müller-Rid and his colleagues (45, 54, 72). A summary has also appeared in an article by Brewden and Locking (50).

Despite all this it is not easy to disentangle from the wealth of data anything of really solid worth. So much of the work has necessarily been undertaken in conditions where it was impossible to check easily the effect of making alterations, and it is risky to generalize too much from improvements reported for individual machines. What follows represents a brief summary of the characteristics reasonably attributable to the various major designs which, for convenience of identification, are sketched in figures 1.9.

1B.4 3 Summary of approach design characteristics

The simplest improvement over the straightforward discharge of the pipe into the bottom of the breast box is the use of a manifold giving several inlets, Fig. 1.9a. In this case the pipe approaches the breast box centrally, or less commonly from one side, and terminates in a short length of pipe under the box from which smaller branches all of the same diameter are taken off as smoothly as possible. This appears to have the same inadequacy as the use of separate discharges from a number of screens; it is very diffi- cult to ensure uniformity of flow in each inlet and discrepancies persist through to the slice. Nevertheless, this is probably still one of the most commonly used approach systems and it seems in practice, with the aid

of suitable baffles, perforated rolls, and evener plates in the breast box, to give a satisfactory performance on slower machines.

The manifold inlet, as with other types, is sometimes associated with a large 'explosion' chamber into which the individual pipes discharge before entering the breast box proper, this is intended to help even out discrepancies in the approach flow. However, this idea has been generally condemned and it is claimed to be impossible to design such a chamber on sound hydrodynamic principles; in practice it is likely to cause considerable instability in the flow due to the formation of large vortices which periodically break away to produce a disturbance.

A development from the manifold inlet design has involved the use of a continuous sub-division of the main pipe into smaller and smaller pipes spreading across the width of the machine, Fig. 1.9b. Though logical in conception this design seems to have proved disastrous in practice, apart from being a nightmare to keep clean. It is, of course, extremely difficult to ensure that flow at a tee-junction splits evenly and periodic surges from side to side can easily occur even, it seems, when some form of streamlining is attempted. With a multitude of splits of this type these surges can apparently become well-nigh uncontrollable.
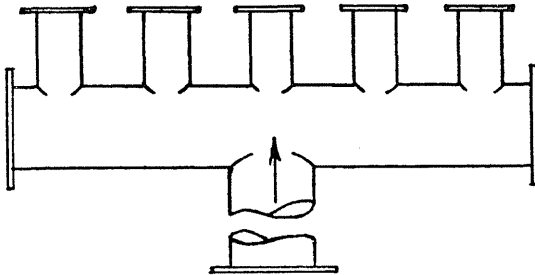
Fig. 1.9a. Simple manifold approach
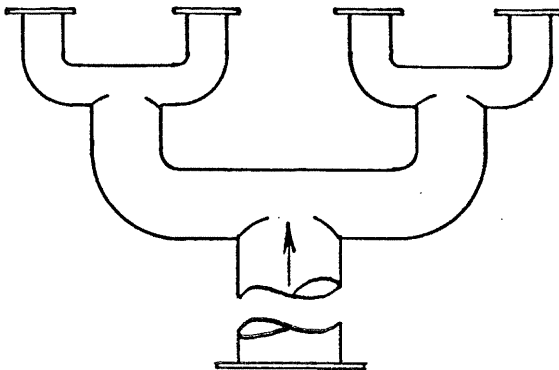
Fig. 1.9b. Multiple manifold approach

43
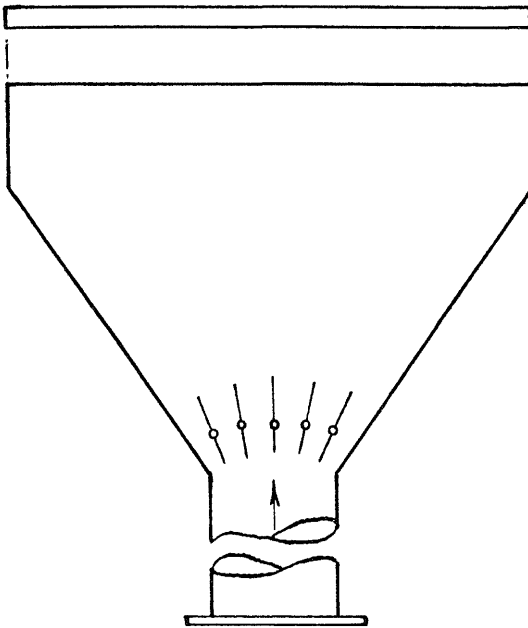
Fig. 1.9c. Wedge flow spreader with guide vanes
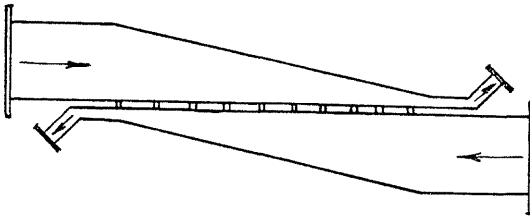
Fig. 1.9d. Cross flow distributor approach

Fig. 1.9e. Tapered side-inlet approach

44

THE WET-END FLOW SYSTEM 1B.43
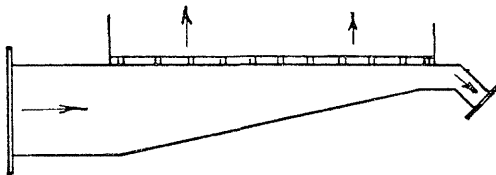
A different approach to the problem is represented by the inlet design involving a gradual change from the main pipe into a narrow wedge equal in width to the machine, Fig. 1.9c. The main problem here is having sufficient space available to allow a reasonably gradual change in cross-section. If the angle of spread is too large (Van der Meer (17), put it at 12 deg., although this has been disputed and 7 deg. seems to be accepted in other industries with a similar problem), then undue turbulence occurs even if the stock is accelerated slightly by carefully reducing the cross-sectional area of the inlet. A perforated roll situated at the inlet to the breast box assists in reducing this turbulence and wider angles seem possible then. Nevertheless, to obtain sufficient length for the gradual change in cross-section it is often necessary to double the inlet over once or twice. This should always be done in a gradual upward direction (requiring height which may not be available) or the whole effect of the design will be easily destroyed by cascading and eddies in the flow. A final point is that this type of inlet, though it has proved quite popular and has been found better than other types particularly by Nelson (55), can be very hard to keep clean and slime is reported to gather easily at points on the wall where flow separation occurs. Guide vanes, as shown in the figure, inserted close to the point where the flow first begins to open out are reported to be helpful in keeping the flow steady and bleed-offs at the side have also been used.

Another completely different type of approach system received much attention some years ago and had several strong advocates. This involves splitting the flow into two pipes which enter at right angles from both sides of machine into a specially designed taper system, Fig. 1.9d. It is known as the cross-flow inlet and several types have been tried. By arranging for the rate of taper from one side to be balanced by the rate of enlargement into the opposite side it was expected that the joint flow up into the breast box would be equal across the width. At first the end of the taper from one side was arranged to allow an overflow into the entry of the opposite taper, but it was found in practice that the flow tended to go in the opposite direction to that intended—from the wide end to the narrow end. This led to the use of an overflow from both sides which was taken back to the mixing pump inlet in the pit. The quantity overflowing has an influence on the performance of the inlet and allows some correction to be made, but despite alteration of this and other parts of the flow it appears that it is difficult to remove three positions of higher pressure at the slice, in the middle and close to both sides of the machine, and to prevent the same sort of pressure fluctuations from side to side that have been observed in other types of approach system. Müller-Rid and his colleagues found the original cross-flow concept unsatisfactory for these reasons, but with extensive experimental work on models later claimed to have developed the arrangement to give much more improved results in full-scale installations; their design also incorporates what they call 'tubular distributors' to even out fluctuations and this seems to be a development of the explosion chamber idea.

Finally, a fairly recent newcomer to approach system designs is the

45

one-sided inlet with a controlled recirculation and a gradual tapering from one side of the machine to the other, Fig. 1.9e. Discharge into the breast box is effected upwards through either a conical plug or a large number of holes or short pipes the diameter of which is carefully selected in relation to their length. This type, though requiring careful calculation of the taper section, is designed to give a cross-web profile which remains very stable when changes are made to the head or backwater flow, a feature which has been confirmed in a number of model and full-scale experimental studies. But the use of an overflow of 15 per cent. or more of the flow, which either requires a separate pump or is returned to the mixing pump inlet in the pit, means a substantial increase in pumping costs. Also a sensitive flow control valve is needed to adjust the pressure difference between the ends of the taper though in practice this does not actually appear to be too critical. A large overflow may also have undesirable possibilities in that any instability in this flow could produce fluctuations in consistency in the system which would affect the substance as changes in retention do.

In sum, it appears fairly easy to design an approach flow system that gives a passable performance so that with some ingenuity from the machineman satisfactory paper can be made; but it is not possible yet to say that any particular design is outstanding, particularly for faster machines where the situation is more critical. The three types that appear to give least trouble are the manifold, the gradual enlargement, and the one-sided inlet with a taper flow; the latter, in particular, has been the subject of considerable development in recent years and is finding much favour for new machines, particularly in the form which involves a rectangular taper and perforated plate. Other types, particularly when a split in flow is required, do not appear to be so stable. As a rule it seems wise to ensure that all flows into the breast box are in an upward direction with a slight acceleration produced by narrowing the cross-section (too great an acceleration can produce backing-up eddies which will be most troublesome). Otherwise the only other obvious necessities are avoidance of spots where slime can collect and designing to permit easy cleaning.

1B.5 BREAST BOX DESIGN

If the approach system were so well designed that the flow velocity is uniform over the whole width of the machine, with no cross-currents and only a relatively small degree of turbulence sufficient to keep the individual fibres in random suspension without flocculation, then the breast box would serve only to provide sufficient head at the slice. As it is, the shortcomings of the approach system necessitate a relatively large reservoir of stock in the breast box and a multitude of devices to help even out unwanted disturbances and poor uniformity. There have been many new designs for breast boxes appearing in post-war years and, as with the approach system, most experimental work has been carried out on faster machines. Essentially the same techniques have been used in investigating breast box design and in addition the use of models and methods of visually

observing the flow have been tried (see for example, Sergeant (6) and Att-wood and Alderson (49)).

It is, however, even more difficult to extract from the numerous reports data which may be safely generalized, particularly since the breast box is judged mainly by its ability to smooth flow fluctuations and the magnitude of these depend very much on how well the whole wet-end system functions. What follows represents a brief summary of what the author considers to be the most important design points and is largely drawn, except where stated to the contrary, from the same articles as those quoted on page 42 for the approach system. For convenience an arbitrary division between low, medium and high-speed machine breast boxes has been taken since the speed, and hence the head required behind the slice, governs the general design of a breast box more than any other factor.

1B.5 1 Low-speed design

For very low-speed machines the old dam breast box is still in common use, yet there has been very little work of value published about it. The head required behind the final slice may need theoretically to be only a matter of an inch or two in order to give a velocity appropriate to the low speed of the wire, and at such low heads there exists an appreciable difference in velocity between the upper and lower planes of the stock issuing under the slice. Under these conditions formation depends less on controlling the level in the breast box, as for faster machines, than on the position of the apron and the shake but this topic will be deferred until drainage and formation conditions on the wire are considered. The position of one or more earlier slices in the breast box does not seem to be very critical and their purpose appears to be mainly to help spread the flow evenly across the machine (since the approach system is generally rudimentary) and to allow the head behind the final slice to be adjusted. A row of adjustable rods of suitable shape may extend across the box in the main compartment to help spread the flow evenly and induce a small amount of turbulence to keep the stock in suspension; bricks and lumps of wood can similarly, though less systematically, be employed. A recent article (59) has gone into the subject in rather more detail and may be referred to for further information.

For speeds much greater than 200 to 300 ft. per minute the comparative crudity of this simple design shows up and it is more usual to find a single slice, of a more developed type (see 1B.6), and a breast box which is more elaborate in construction. Nevertheless relatively low heads are still required to suit machine speeds under about 500 ft. per min. and create a difficulty if the volume of stock in the box is not to be too small for adequate time to be available for spreading and evening out the flow. Where a perforated roll is used it is preferable to have it submerged to avoid flocs developing; this may necessitate curving the bottom of the box upwards to the slice. Apart from this the problems encountered are essentially the same as for medium-speed boxes and these will now be considered.

1B.5 2 Medium-speed design and general comments

The general principle adopted in most straightforward breast boxes is to direct the flow entering the box upwards to a level which gives sufficient head behind the slice and to divide this flow from the slice by a baffle extending from the bottom of the box up to somewhere near the surface level. This serves to reduce the effect of inlet disturbances on the pressure at the slice and often the flow may be directed under and over a further pair of baffles for the same purpose. But it is not desirable to have the length of the box too great because this will lead to large volumes of stock moving at a comparatively slow velocity in the box and it then becomes easier for dead spots, settling, aeration and flocculation to occur given sufficient time. If the approach system is satisfactory a single baffle dividing the upward entry flow and downward flow to the slice should be all that is necessary. A moderate amount of small-scale turbulence is suitable though in appearance the flow should be fairly streamlined and there should be no eddies; it can be useful in this respect to build out the edge of baffles on the trailing side into a streamlined P shape because where the stock flows under or over the edge at relatively higher velocities eddies tend to form in the lee. The flow down to the slice is preferably accelerated slightly for better control and to keep the turbulence scale down to a minimum; this may be achieved by humping the bottom of the box so that the cross-sectional area can be narrowed slightly approaching the slice, but provision may then be needed for draining the box when the machine is shut. Especially with a vertical front wall to the box, at fairly low heads small vortices may form when there are excessive cross flows and this is very detrimental to formation at the point on the wire opposite the vortex. Numerous designs which follow, more or less, these precepts are on the market and a useful comparison of the main varieties may be found in reference 85.

The necessity of having the breast box easily accessible for cleaning is well recognized yet it is surprising how often with faster speed designs that it proves difficult in practice to accomplish this without practically dismantling the box. Joins, welds and gasketed strips have to be carefully finished off or they readily form a place for collecting slime and fibre lumps which cause holes in the paper when they break away. Wooden boxes also easily collect slime and cast slivers so that most non-metal breast boxes nowadays are lined in copper, rubber or thermosetting plastic. Polished stainless steel is more commonly used for breast boxes though plastic, in particular unplasticized P.V.C. strengthened by layers of resin-bonded glass-fibre, gives a smoother surface and is easier to keep clean than a similar-priced finish in steel. The upper surfaces of completely closed boxes, and behind the top lip of a projection slice, are also likely to get very dirty, especially when the stock is aerated; occasionally stock is bled off upwards at suitable points where air could collect but unless air gulps at the slice this may cause more trouble by disturbing the flow than if the air is allowed to remain. Some boxes have an overflow for the removal of excess stock together with froth on the surface but sprays are generally considered better for this purpose.

Many breast boxes possess a large dump valve for diverting the full flow to the pit for a quick inspection of the wire part without interfering with the flow through the mixing pump and cleaners, and this requires careful attention if it is neither to clog up with fibre nor act as a slime trap. There is some merit in siting the valve outside the box proper but this depends on the general layout. One useful solution is to insert a specially-designed dump valve (streamlined to avoid interfering with the flow) followed by a gate valve in the main approach pipeline; if these are pneumatically operated it is then convenient to arrange for a single switch to close the gate valve and simultaneously open the dump valve, diverting the flow into the back-water pit instead of the breast box (a helpful adjunct is to have the fresh stuff valve automatically closed at the same time to prevent thickening up the pit).

1B.5 3 Breast box equipment

The perforated roll has proved a very successful device for assisting in dispersing the fibres and inducing a degree of small-scale turbulence, while at the same time damping down larger eddies. It can be used with advantage for evening out where the flow enters the box and it then becomes, in effect, part of the approach system. The perforated roll is also used very frequently just in front of the slice where its main purpose is to impart a final small agitation to the fibres in an endeavour to spread them evenly throughout the flow, particularly in a vertical direction; the roll is also thought to help reduce any tendency to flocculation due to the high shear forces experienced as the stock is accelerated through the holes, and this has been confirmed in experimental work by Mardon *et al.* (91). This particular reference presents a thorough-going analysis of machine experiences with perforated rolls in addition to experimental results, and is drawn on considerably in what follows. As the perforated roll nearest the slice has the greatest influence on the characteristics of stock in the slice jet, attention is concentrated on this particular application.

There are so many variables involved with a perforated roll that it is extremely difficult to reach any general conclusions on its performance. Mardon distinguishes between two basic effects of the roll: the hydro-dynamic which relates to the smoothness of flow from the slice, and the papermaking which relates to the degree of deflocculation and absence of fibre clumps resulting from using the roll. Often it is found that require-ments for hydrodynamic stability and for papermaking are directly oppo-site, and choice of dimensions and other features of the roll becomes a compromise based on inadequate detailed information. The variables associated with perforated rolls are mainly the position relative to the slice, hole diameter, open area, and speed and direction of rotation. Each of these will be discussed briefly.

If a perforated roll is too near the slice streaks and other disturbances are more apparent on the wire. These disturbances, known generally as the 'wake effect' of the roll, are enhanced when there is discharge from the breast roll. Mardon quotes an empirical formula for the minimum distance

behind the slice at which to place the roll to avoid the wake effect, and gives several examples illustrating its application. The formula indicates that the distance required between the roll and slice increases for larger hole diameter, smaller roll diameter, smaller open area and greater flow velocity through the roll. Elsewhere a useful rule-of-thumb guide for the minimum distance is given as the equivalent of twenty hole diameters.

From the hydrodynamic viewpoint the smaller the hole diameter the less likely it is that any wake effect occurs. But Mardon found that smaller holes produce less deflocculation downstream of the roll, though this effect also depends on the velocity of flow through the roll and at lower velocities is not so prominent. He advises that generally the smallest holes practicable should be used, though to avoid other disturbances referred to below it may be necessary to use holes up to 1 in. in diameter. A compromise is needed with the flow velocity because although when this is lower it is less likely to cause the wake effect, it also gives more time for reflocculation to occur downstream of the roll. Mardon found evidence for the existence of a critical velocity above which the stock would flow for a considerable distance in a deflocculated state; for a mixture of softwood and hardwood kraft this is about 1·0 feet per second.

The questions of open area of the perforated roll and speed of rotation are ones that have received the attention of several workers. Bennett (29) carried out experiments using air as a medium (even allowing for the appropriate scale factors some care must obviously be taken before extending these results to a fibrous suspension), and found that although the usual design of perforated roll is good for levelling non-uniform flow, the degree of solidity should not be greater than 50 per cent. or instability is likely to occur. This confirmed an earlier statement by Van der Meer (17) who advised use of a roll more than half open for inducing microturbulence, otherwise uncontrolled merging of streams on the downstream side of the roll creates large scale turbulence. Nelson (55) on the other hand has reported that a 60 per cent. solid roll was good at evening fluctuations, which is in direct contradiction. Mardon has presented the most detailed comparison of rolls with different open area and his conclusions are that rolls away from the slice should generally have 40 per cent. open area, whilst those just ahead of the slice are best made with about 48 per cent. open area unless long fibres are involved in which case the open area is best reduced to 43 per cent. or lower to lessen the risk of stapling of fibres across the land gaps.

Rotation of the roll is important from the point of view of keeping it clean and although Bennett found that rate of rotation had no effect there is now evidence that the flow is disturbed if rotation is too great. Wrist (74) found that a slow rotation can produce large flocs that pass unbroken through the slice while too fast a speed of rotation increased turbulence and instability of the flow; he considers that a variable speed drive for a roll at the slice position provides a valuable control on the performance. Mardon again in two papers (83, 91) investigated extensively the effect both of speed and direction of rotation. He reaches the conclusion that speed is not too critical so long as it is fast enough to avoid stapling of

fibres, but not so high that hydrodynamic disturbances occur and show up as deep ridges in the flow from the slice. It is usual to rotate the roll against the flow at the bottom to reduce the possibility of approach system disturbances passing straight to the slice. This also reduces the severity of fibre clumps caused by fibre 'scooping' on the trailing edge of the holes and then breaking away on the downstream side. 'Scooping' of fibres is worse at higher speeds of rotation (in contrast to stapling effects) and with smaller diameter holes.

Various constructional details of perforated rolls are important. The gap between the rolls and the walls of the breast box must be even and narrow otherwise unstable flow conditions can occur and too much stock can by-pass the roll without meeting shear forces in the holes. When a roll is situated in the body of the box it is often considered preferable to keep the level just above the top of the roll in order to reduce any by-pass flow but prevent the possibility of aeration; on the other hand many paper-makers prefer to have the roll just above the level so that the presence of fibre on the land areas can be seen. Holes must be pitched in a spiral pattern to equalize their effect across the machine, and according to Mardon it is preferable for rigidity to make the roll from a drilled tube and have a reasonable wall thickness radiused off to not greater than $\frac{1}{32}$ in. Discs in the roll assist in damping down cross-currents and can be spaced as little as $1\frac{1}{2}$ inches apart; they should be perforated to allow some cross-flow to take place. Construction of the ends of the roll is particularly important and in this respect there has been some difference of opinion regarding how close to the wall the holes in the roll should extend. Some have considered that leaving a solid space at the end will cause the flow on the downstream side to rush into the walls thereby overcoming the slow boundary layer which can reduce substance at the edges. However, apart from the fact that the roll should be far enough back from the slice to eliminate influences of this sort, all that seems likely to happen is that undue turbulence will be created at the edges making substance there variable. The roll should in fact be identical in construction along its entire length and various designs conforming to this requirement are given by Mardon.

Other devices have been used to even out flow and damp down turbulence in the breast box, including stave rolls (constructed from a number of long thin rods stretching across the width of the box and held together at intervals by discs), pear-shaped deflectors, 'homogenizers' (angled plate fins on a tubular shaft) and evener plates. Reitzel (45), has described the use of stave rolls in the approach system of a specially designed box where he claimed that they prevented alignment of fibres in a converging flow and were easier to manufacture and keep clean than a perforated roll. The stave roll could not, however, be used near to the slice otherwise marking of the sheet occurred and in a more recent modified breast box designed on similar lines this type of roll has apparently not been used. Evener plates or flow eveners are in general use to reduce cross currents close to the slice in the breast box; the trouble with these is that channelling is likely to occur producing permanent streaks in the paper and it is

normally considered inadvisable to use flow evener plates without following them with a perforated roll to overcome this effect. Alternatively, Wrist has claimed that temporarily narrowing the passage by using a stationary cylinder or solid projections on the walls close to the slice is more beneficial in this position though other reports on this device have indicated that excessive turbulence in the slice jet may be induced (82). The edges of the individual plates should be rounded to prevent stapling of fibres and it is essential that the plates fit snugly into the breast box walls.

1B.5 4 High-speed boxes and designs for a wide range of speeds

The pressure required behind the slice for machine speeds of 1,500 ft. per min. is equivalent to about 12 feet head and the design of a satisfactory breast box to give heads of this order presents many difficulties. The air-loaded box has been very successful in providing a way out of this difficulty and many types are now in use. The basic advantage of an air-loaded box is that the lower stock level gives a more controllable flow to the slice. On the other hand, air-loaded boxes are more sensitive to pressure changes in the approach system, and although the actual stock level in the box alters less than for an open box working under similar conditions, the change in total head at the slice (and hence of stock velocity from the slice) is much greater than with an air-loaded box.

The most common device for stabilizing the operation of an air-loaded box is the so-called Hornbustel hole which allows a mixture of stock and air to be continually bled off from the side of the box. The stock level in the box stabilizes at the height of the hole and effectively prevents the water/air surface from the violent fluctuation in level which occurs in a completely closed and uncontrolled system. To obtain a greater head at the slice, all that is necessary is to increase flow from the mixing pump and a new equilibrium condition is eventually reached with the same stock level but greater air pressure in the box. It is a valuable asset to be able to adjust the level of stock in the box in order that velocity of flow to the slice can be varied though frequently the range of machine speeds and breast box consistency is sufficiently narrow to make alteration of the level unnecessary. With a simple hole in the side of the box adjusting of level is not possible, but there are several simple modifications providing this facility and these include placing the hole eccentrically in a rotatable flange, using a vertical tube adjustable in height in place of a simple hole, or employing a float system operating on a needle valve to regulate the air bleed-off.

In an analysis of the stability of different types of air-loaded box control systems, Mardon *et al.* (90) points out that with the Hornbustel hole the slice head change resulting from a given increase in stock flow to the breast box can be considerable. This is because if the stock level rises, air pressure must first build-up in order to reduce the level to its former position, thus magnifying the original head change. Hunting is very easy to obtain if the size of the hole and setting of the air input pressure are not

carefully matched. In practice some difficulty can be experienced in obtaining a smooth bleed-off which does not gulp periodically and cause a violent change in head.

A different approach to the problem of achieving stability of air-loading is to control the level in the breast box by automatic adjustment of the main stock flow control valve on the discharge side of the mixing pump. (Alternatively control can be on a bypass round the main stock flow valve or on a recirculation line round the mixing pump). To detect the level position in an air-loaded box a differential pressure cell arrangement is used. The total head at the slice is measured and controlled by regulating the air pressure in the box either by direct adjustment of a valve on the supply line or by adjustment of a separate air bleed-off also on the supply line or on the box itself. With this arrangement, if for example a greater head is required at the slice, then the air pressure can be increased, thus depressing the stock level causing a compensating action on the main stock valve which opens until the additional quantity necessary to maintain the level is reached.

According to Mardon, this system is not stable because although an increase in flow to the box causes level to rise thus producing a closing action on the flow control valve, air pressure will also reduce due to the control action initiated by the rise in total head, and this will tend to counteract the first action; thus hunting is readily set up. A better system for stability is to control the total head by adjusting the main stock flow valve (as is in effect done with an open box), and control the level by adjusting air flow (possibly retaining the Hornbustel hole for this purpose). Provided a three-term controller is used on the stock flow valve, this system can give very good stability if properly set up. Although in theory it should be possible with either of these systems to run at very low machine speeds by applying a vacuum instead of pressure to the air chamber this does not in practice appear to work very satisfactorily.

Another design which has met with some success and which departs completely from the air-loaded pattern is the flow nozzle. In this type there is no large reservoir of stock or air-chamber giving a cushioning action in the breast box, but instead the flow is direct from the pump through the approach system to the slice and always under pressure. A refreshing and frank account of the difficulties encountered in taking a design of this type from the drawing board to the machine is given in the paper by Reitzel mentioned above. Apart from designing the nozzle to permit adequate cleaning and avoiding horizontal upper surfaces on which slime can collect, one of the main problems in practice is to prevent hydraulic fluctuations from reaching the slice when there is no natural damping available as in normal breast boxes. However, this difficulty has been overcome adequately even without use of a surge tank which has been advocated by several writers, and it is very likely that on faster machines a modification of this type of box could prove useful. There are also some designs for tissue manufacture where the sheet is partly formed on the wire within the box itself and also the 'frozen-flow' box in which stock is conducted through a large number of 4 in. copper or plastic tubes extending

3   53

well into the box, but these are too specialized or too little known about for consideration here.

One advantage of both the air-loaded box and the flow nozzle is that both are readily adapted for varying machine speeds. The difficulty here is often to maintain adequate depth in the box at low speeds while preventing sluggishness in the flow. The problem of depth is solved satisfactorily in air-loaded boxes though the flow will tend to become too slow for low machine speeds; in the flow nozzle this is apparently not so much of a difficulty. On boxes of conventional design an attempt is sometimes made to run at lower speeds and at the same time to keep up the level of stock in the box by interposing in the section of the box leading to the slice a means of throttling the flow; this may be in the form of rubber restrictors or possibly by means of a specially designed sliding gate valve. This solution suffers from the considerable disadvantage that it is almost impossible to avoid interfering with the flow pattern at a critical point and the uniformity of the sheet is liable to suffer; also the presence of air in the stock can very easily cause trouble.

1B.6 SLICE DESIGN

Adjustment of the slice across the machine is the only way in which deficiencies of flow uniformity in the approach flow system and breast box can be removed, and once stock has flowed through the slice no further correction to the dry weight of the paper across the machine can be made. Apart from this highly important aspect, the slice opening in relation to the pressure head determines the volume flow, and hence the consistency of the breast box stock, while the relative position of the lips is critical for assisting in formation of the sheet on the wire in the early stages. This latter topic will not be dealt with in detail, since it is more appropriately considered as a part of the wire section in Part 3, and only the general character of the slice jet itself will be covered here.

1B.6 1 Vertical slices

With the old double-straight slice no proper adjustment of the cross-machine substance is possible (unless sticking pieces of paper underneath the slice is considered adequate). For that reason an adjustable form of vertical slice has replaced the rigid slice on most older machines and this allows the substance to be altered more easily across the machine. More advanced designs of breast box for medium speed machines are also sometimes fitted with vertical slices, but they have not received as good a reception as the projection slice. The main reason appears to be that adjustment of the slice blade in a vertical direction introduces stresses which can easily lead to buckling of the blade; this is particularly the case where large temperature changes occur and in addition it is generally necessary to change the blade on the slice at fairly frequent intervals.

The vertical slice is usually situated directly above the end of the bottom lip or apron and this gives a jet which is roughly horizontal. The coefficient

of contraction is, however, much lower than for a projection slice (about 0·7 compared to 0·95 or more) which means that higher heads behind the slice are necessary. Although the jet is probably more stable close to the slice the large increase in velocity up to the vena contracta will make the actual velocity of impact with the wire for a given head very sensitive to the width of the gap over which the jet travels after leaving the slice orifice. It is generally considered that the substance across the machine can be adjusted more accurately with a vertical slice and in a report by Müller-Rid and Pausch (45) this was confirmed; these authors tried out both a projection slice and a vertical slice on a machine and both tests for uniformity of substance and formation across the sheet and the subjective assessments of the machine crews agreed that adjustment was achieved more rapidly and accurately with the vertical slice.

The same authors report similar tests using a combination of the projection and vertical slice. In this design a thin blade is attached vertically to the end of the upper lip of a projection slice and protrudes a fraction of an inch below the lip; this blade is used for adjusting cross-machine differences rather than the upper lip itself. This modification proved more successful than either the straightforward projection or vertical slices and was chosen as the most suitable method of adjusting the slice. It is now being used increasingly on new machines and the blade has been christened a 'profile bar' or, with a curious sense of inappropriateness, a 'spoiler'. The main difficulty encountered with this idea is that fibre tends to collect on the edge of the vertical slice; with long-fibred stock it becomes hardly practicable to use it. It would appear also that the extent by which the vertical blade protrudes below the upper lip is critical and it should ideally only skim off the boundary layer, where the velocity is lower; if the blade extends too far into the gap formed by the main lips turbulence can be expected at a critical point in the jet and this would be most undesirable.

1B.6 2 Projection slice

The projection slice is by far the most common in use and despite its well known weaknesses it is generally considered the most reliable type. A substantial amount of work has been done in investigating flow from this type of slice and this will be drawn upon in what follows; apart from the results of Müller-Rid and his colleagues mentioned above, this work has been reported, except where stated, in the papers already listed on page 42 when describing approach flow systems.

First, a few general remarks on the projection slice. It is particularly important that the slice edges, especially the upper lip, are kept clean, and this is much easier if they are rounded slightly. Another reason for avoiding sharp edges is that instability of the flow is more likely to occur due to the sudden separation of flow at the end of the lips, but on the other hand if the bevelling is too great air is liable to gulp back causing a disturbing jump in the jet. The inner surfaces of the slice lips should be very smooth and it is important that there should not be a sudden discontinuity where

the lips are attached to the breast box. With the upper lip this is usually difficult to avoid since the lip is arranged to pivot about the end point; however, in the paper by Reitzel an attempt to overcome this by using a flexible joining strip is described and appears to have been successful.

In some types of projection slice, notably the Van de Carr, it is usual to slope the wall of the breast box down to the slice. Though this seems an eminently sensible idea to encourage a smooth flow to the slice and at lower heads should reduce the risk of vortices forming (as occurs with vertical walls), the sloping front wall has met with some criticism. It is apparently difficult to predict the degree of slope required and Mardon and Van der Meer (12) in particular indicate from their experience a strong preference for the vertical wall. For stable flow the angle between the lips should, according to Van der Meer (17) be between 10 deg. and 20 deg.

1B.6 3 Adjustment of the upper lip

The position and operation of the individual jackscrews on the upper lip is very important since it is their efficient functioning that governs how easily a uniform substance across the web is achieved. The flow issuing from any particular point across the web spreads slightly and intermingles with adjacent streams; this has been shown clearly by Sergeant (6) who added a thin stream of dyed fibres just after the slice and found a distribution in the reel-up spreading over a width of several inches, and also by Mason *et al.* (14) who used radioactive-tagged fibre in a similar manner and obtained a normal distribution in the reel-up spreading over $3\frac{1}{2}$ in. to 5 in., less than in Sergeant's work but this was on a faster machine. Normally the jack-screws are arranged at 5 in. to 6 in. intervals, which should therefore be adequate for adjusting the substance accurately.

Unfortunately, as is well known, alteration of one screw causes stresses in the blade which alters the position of adjacent screws. Cuffrey (30) has investigated this effect in some detail and found, for example, that a drop in one screw giving the equivalent of a 4·5 per cent. weight change caused the adjacent screws (set at 4 in. intervals) on either side to drop also, though to a lesser extent; however, as far as three screws away there actually occurred an increase in substance equivalent to as much as 3 per cent. Though severe there was no doubt that this effect was due mainly to the slice blade flexing and only partly to diversion of the flow outwards at the slice and on to the wire on either side of the restriction. Some other experiments reported by Cuffey are illuminating in illustrating the difficulties that face machinemen in adjusting cross-level on a normal projection slice. In one case individual jack-screws were adjusted from front to back of the machine; when this was completed it was found that the front settings were no longer correct by a comparatively large margin. Even when set as near as possible during a shut period, when water was run through the slice under the usual running pressure of under 20 in. head the slice opening increased more in the centre than at the sides necessitating the resetting of screws at the sides by as much as 15 thou. Some weaknesses in the

usual worm gear and offset cam arrangement for lifting the whole lip were also found; for instance, the front side dropped much more than the back when the overall slice gap was reduced and this would have produced a lighter sheet at the front compared to the back. For small movements of the whole lip the back of the slice could actually go in the opposite direction to the front depending on the direction from which previous movement was made.

Machinemen are generally aware of the lack of reliability in adjusting the whole of the slice gap and know that doing this is liable to upset the cross-level substance. For this reason there is a definite reluctance to alter the slice gap when a change in the amount of backwater used for dilution is required and the head behind the slice is allowed to alter instead. As already discussed, this is a bad practice except possibly for very small changes and it would appear most desirable to effect an improvement in design of the mechanism for altering the slice lip, possibly along the lines suggested by Reitzel in his paper.

Another problem associated with the slice is that of obtaining uniform substance right to the edges. In practice, because of the slowing down of flow at the edge walls of the breast box and slice, the substance tends to be light at the edges and some undesirable bow waves can be formed on the wire. A common practice to overcome this is to lift the slice slightly at the edges. This would appear a more satisfactory solution than attempting to influence the rate of flow at the edges of the slice either by leaving out holes in the perforated roll at the edges, locating the deckle a little in from the slice edge, or attempting to divert some of the flow towards the edge by means of a small obstruction projecting from the side into the slice. All of these methods are frequently used but may be liable to induce too much turbulence, making the setting critical and giving a variable performance. Another popular method of overcoming the edge problem is to bleed off a small quantity of stock at the edges of the slice; however, some recent work by Mardon and Wahlström (53) indicates that the bleed-off may have the opposite effect to that desired—closing the flows off could actually cause an increase in pressure, and hence in substance, at the slice edges, rather than the decrease expected. The position of the deckles should coincide with the slice edges to minimize turbulence and this is one very strong reason why even on very slow machines it is usually better to avoid changing deckles and instead to run a trim down into a hog pit. Even if flow from the slice were perfect it would not prove possible to form a perfect sheet right to the edges of the deckle because stock will tend to climb up the edge inducing a wave across the wire. The main object of the machineman should be to confine these disturbances to as narrow an area as possible so that low-quality paper at the edges is removed in the trim; this must be done by trial and error for each machine by observing the effect of the adjustments available on the dry-line and the general smoothness of flow at the edges.

During a shut period it is common practice to set the slice by means of a taper gauge, but this is inadequate in several respects. Even if the setting is done with sufficient care to get the gap as accurate as possible all the way

across, once the slice gets heated with stock and pressure forces up the middle more than the edges, the gap between the lips across the machine may be extremely variable. To all intents and purposes this implies that the substance also will be variable in the same way since at any point across the machine this depends essentially on the width of the gap (Attwood and Alderson (49) exhibited this rather neatly by using a suspension of polystyrene pellets in water through a model slice—the number collected at any part of the slice followed almost exactly the width under pressure of the slice gap). Perhaps the only method which achieves a reasonable degree of accuracy is to study flow from the slice with water heated to the normal running temperature and working with the usual head behind the slice. Provided sufficient time is allowed for the whole slice to achieve normal operating temperature (and this may be sometime if the slice and breast box has cooled down) observation and measurement of the volume flows across the slice will enable the jack-screws to be adjusted closely to normal operating conditions as well as exhibiting other deficiencies in the flow. But this procedure can only be done with the wire removed and even then measurement of the flow at different points across the machine is far from easy to manage, so provided an adequate and rapid means of assessing the cross-web substance profile is available to the machineman (this is considered in more detail in 1C.3 4) then it will generally be more satisfactory to continue with a relatively crude preparation and then to adjust the jack-screws as quickly as possible once the machine is under way.

1B.6 4 Character of the slice jet

Some detailed studies have been made of the character of the jet from a projection slice in relation to the position of the lips. Mardon and his colleagues have presented a wealth of data obtained on different machines in the course of their investigations and have exhibited how pressure varies through the thickness of a slice jet; their general findings in this respect have also been confirmed by Attwood and Alderson. Close to the lips the pressure, and hence the velocity, of the flow is lower due to boundary layer friction. This area of low velocity extends only a short distance from each lip but is nevertheless thought to be responsible for some of the instability and fluttering of the jet that has been observed on faster machines. Small obstructions in the slice are less liable to create turbulence when the boundary layer is thin; the boundary layer thickness is increased by roughness of the slice lips but the presence of fibre helps to reduce it and makes the jet more stable. Apart from this effect, which is confined closely to the top and bottom of the slice, the pressure through the thickness of the jet is pretty well the same except for a slight increase towards the bottom of the jet due presumably to the slightly greater pressure there. Further details can be obtained on this topic in an article by Mardon and Shoumatoff (25).

The positions of the top lip and the bottom lip or apron in relation to each other and to the wire are very important. Normally the apron is

horizontal and the top lip angled downwards, though in some cases the apron may also be directed downwards when rapid drainage is desired. If the top lip terminates directly over the end of the apron then the jet as a whole has a slight downward velocity. The further the top lip is moved back in relation to the bottom lip the more horizontal becomes the jet, at least up to a point where instability may occur due to prolonged drag on the apron. Normally it is considered that the more horizontally the jet hits the wire the less will be the disturbance, and it has been recommended that a good compromise is achieved by having the top lip back from the apron by a distance equivalent to twice the slice opening; according to Nelson (55) this also has the advantage that the jet angle is not so sensitive to variations in slice opening. If the top lip terminates above the apron, a horizontal jet can only be obtained by sloping the apron upwards. On some machines the lack of drainage capacity necessitates removing the water as quickly as possible and in this case it is usual to direct the jet downwards to give greater impact and initial drainage. The position of the end of the apron controls the point at which the stock hits the wire although, of course, this is also affected by moving the top lip (if this is moved back, up to a certain point the jet will carry further down the wire). If rapid drainage is desired the jet is made to hit the wire close to top dead centre of the breast roll which will then remove a lot of water, but generally speaking this will reduce the chance of getting a clean formation because the jet is violently disrupted by the suction forces of the breast roll before it has settled even slightly on the wire. Since it is the formation which is affected primarily by this it is appropriate to leave this topic for closer consideration in Part 3.

1B.7 AERATION OF THE STOCK

It has long been recognized that an excessive amount of air in the paper stock at the wet-end is undesirable, mainly because froth is more likely to become troublesome under those conditions and in some installations there may be difficulties with depriming at the mixing pump. During the last few years, however, it has become apparent that aeration causes many more effects than these and most of them are detrimental in some way to efficient running of the wet-end. The development of a simple apparatus for measuring the volume of air in a sample of paper stock by Boadway (23) has assisted in stimulating investigations into this problem and since then there have been several useful reports of work in which either the instrument of his design or a modification of it has been used. In addition on several machines application of the deculator, a device which deaerates stock very efficiently, and other methods of de-aeration have shown up differences in behaviour of the stock caused by the removal of air.

1B.7 1 Nature and effects of air in paper stock

There is some difference of opinion regarding the precise definitions to be applied to distinguish between the various ways in which air is held in suspension in paper stock. In descriptive terms the analysis used by

59

Gavelin (11), Jacobsson (19) and other workers seems most convenient and in this the air is divided into three main classes: free, residual and dissolved. Free air represents air which will settle out and bubble to the surface if the stock were allowed to settle; it is primarily responsible for foam and reduces in quantity with depth. The definition is a rough one in that if the stock were allowed to stand the volume of air remaining would reduce for a long time; thus Gavelin found that some breast box stock retained 0·25 per cent. of air after one minute but only 0·1 per cent. after a much longer time. Although free air can disturb flow on the wire and seems to accentuate pitch and slime trouble, it is not thought likely to affect drainage and formation directly.

Residual air does not settle out and may be thought of as being intimately in contact with individual fibres. It is considered to originate largely from mechanical dispersion of free air in refining and other sources of vigorous agitation but may amount to only 0·1 per cent. by volume of the stock; however, even though this seems a very low percentage, it still represents a substantial proportion of the volume occupied by the fibre in breast box stock which, if the consistency were 0·4 per cent. would be only four times as great. The effect of air in this form is more critical with regard to drainage on the wire where the presence of air in capilliaries will affect the water flow and retard drainage. It also can be expected to decrease the effective specific gravity of fibres, affecting their settling rate and increasing any tendency towards flocculation in quiescent regions because of the different rates of settling or even of buoyancy between individual fibres. Surface tension forces in air bubbles contacting fibres that have coalesced will increase the strength with which they are held together and this also will increase the degree of flocculation.

Dissolved air is regarded as air which is held within individual fibres and derives primarily from the fibres themselves in the form of air and carbon-dioxide. It is not regarded as important unless, due mainly to beating action, fibres become saturated with air and bubbles then take the form more of residual air on the surface of the fibres.

The apparatus designed by Boadway for measuring air in paper stock can easily be used with a little practice and subjects a fixed volume of the stock to a given vacuum; the change in volume due to expansion of the air is measured and the percentage of air in the stock can then readily be calculated. The determination includes both free and residual air in the stock but not air in the dissolved or combined state. In practice the amount of residual air at the wet-end of a paper machine (as assessed by other methods) does not appear to alter substantially except possibly at the mixing pump where the percentage of free air may increase at the expense of residual air and of residual at the expense of dissolved air; by far the biggest volume of air, and the cause of most variation in air content, is due to the free air. The sources of this free air and its relation to foam development will now be discussed.

1B.7 2 Free air and its causes

A certain amount of free air may be expected in the fresh stuff from the

preparation system but most is developed at the wet-end itself. The main sources, not in order of importance, may be listed as due to cascading flows (in mixing box, approach system and wire tray discharge), falling through the wire (especially if trays are not used and the backwater falls direct to a wire pit), insuction of air in mixing pump glands, open pipe discharge into tanks (these should be below the surface level), insuction in vortex cleaners with an open reject orifice, and excessive eddies and vortices in tanks, breast box, etc. open to the atmosphere or in channels and half-full pipes. Careful design can obviate most of these causes and the whole backwater system should be organized with these requirements very much in view; this has been done, for instance, on a machine started recently where a specific objective in the design stage was to site chests and pipe lines to minimize cascading while the main whitewater chest surface was made as large as possible to help air to settle out (48).

In addition to these more obvious causes of aeration some recent work by Mardon *et al.* (40, 88) has brought to light other less suspected sources. The air content in breast box stock was found, for instance, to depend on the depth of backwater in the wire pit, the shallower the depth the greater the aeration. In addition discontinuities in velocity and pressure in pipes, valves, tee branches, etc. were shown to affect the air content considerably. Apart from this, the separation of air into a separate phase produces surges in the flow which are detrimental to stability and Mardon demonstrated that reduction of free air in the system helped to lessen the effect of these disturbances on the weight of the paper. This topic will be dealt with in greater detail in **1B.8**.

Brecht and Kirchner (44) determined the air content of stocks for a variety of papers and found an enormous variation from as little as 0·1 per cent. for parchment to 4 per cent. for newsprint and 4·5 per cent. for tissue. The latter figures are of the same order as those reported by other workers mentioned earlier. The air percentage in the stuff chest of one machine was 2 per cent. while that of the table-roll backwater was 11 per cent., thus confirming that backwater is the main source of free air. It was also found that different pulps have a different propensity for entraining air under mechanical agitation: for instance, groundwood fibres were particularly prone to collect air. Drainage rates were slower with more aerated stock while laboratory handsheets exhibited a reduced wet and dry strength.

Reduction of air in stock has other important effects besides those already mentioned and of these lessening the development of foam is one of the most important.

1B.7 3 Foam at the wet-end

The use of devices for removing air in the approach system of the paper machine has demonstrated that foam does not form unless air is present in the stock. Nevertheless on a machine which is plagued with this common source of trouble it is not immediately helpful to the machineman to be told that the stock is becoming too aerated and the design of the wet-end

needs overhauling, as will almost certainly be the case. Various defoaming agents, usually containing a sulphonated oil, are available, but their use should be regarded as an uneconomic stop-gap. Normally pulsating or rotating sprays in the breast box are most useful for preventing the foam growing to such an extent that it breaks away and the paper becomes affected; skimming off the surface in the breast box and backwater pits also helps though there are usually practical difficulties.

Foam becomes worse under certain chemical conditions such as are caused by insufficient washing of a pulp, excess alkalinity, high pitch content pulps, high rosin size concentration or when lime salts exist in the water (47). Higher temperatures may also be expected to increase the likelihood of foam because the air then settles out easier. Fillers do not give much foam except, according to Brecht and Kirchner (62), satin white, and even in this case foam did not occur at a suitable pH. The same workers developed an experimental technique designed to assess how readily pulps took up air; this involves blowing a given volume of air through the pulp suspension with simultaneous agitation and then measuring the subsequent air content. Basic and acidic dyes both usually caused extensive take-up of air and also produced a foam which was comparatively stable, i.e. would not disperse so readily once formed. Direct dyes, however, were mainly without effect. A large number of sizing agents all affected the development and stability of foam. The effect of the circulation water pH was also investigated though this cannot easily be extended to machine conditions; it was found that air was absorbed most easily at a pH of 5·5, and was at a minimum at a pH of 4·5, though the foam tended to become more stable the lower the pH.

1B.7 4 Removal of air in paper stock

The deculator has proved very efficient for removing air in the stock and its design and use has been described in detail by Jacobsson (19) and others (8, 38, 42). The device involves the spraying of jets of stock onto plates in a cylindrical tank under a vacuum which is within 0·1 in. to 0·3 in. Hg of the boiling pressure corresponding to the stock temperature. This succeeds in removing the free air and most of the residual air in the stock. It is obviously necessary to treat all the breast box flow and not just the fresh stuff because it is the backwater used for dilution that contains the higher percentage of air. Thus a rather expensive installation is required and apart from the vacuum pump it is frequently necessary to use two stock pumps, one to mix the stuff and backwater and provide pressure to the de-aerator (and in some cases also the stock cleaners), the next to provide pressure in the normal way to the breast box.

Another form of de-aerator is the Vorvac system which is claimed to remove air from the stock in association with a type of cleaner developed from the older Vortrap design. Also 'eductors' can be fitted to the reject orifices of cyclone cleaners for the same purpose. Both these devices originated from the observation that the high rotational forces and general turbulence developed in the cleaners produced an increase in aeration in

the stock. Their use may well reduce this effect considerably but to the author's knowledge no experimental data has been made available to show whether the amount of air left in the stock is of the same order as with a device working on the principle used in the deculator.

The result of de-aerating stock in a deculator is very marked. Foam is absent and no showers are necessary in the breast box; the suspension settles quickly in the absence of turbulence leaving water on the surface. Slime grows in the usual places but almost no fibres adhere to it and the slime appears to stick to surfaces more firmly; this reduces the likelihood of lumps breaking away. The slice jet is smoother and on the wire the stock looks more glassy in appearance and drains faster than usual (this has been confirmed experimentally by Gavelin (11) using a specially designed drainage tester). Quicker drainage on the wire enables a better sheet to be formed or the machine speed to be increased; in the former case a reduction in porosity, increased smoothness and better printability of newsprint have been reported. These advantages seem at first sight to be considerable, though as with all devices like this economic justification is not easy without a knowledge of the likely improvement on any particular machine. On most machines troubled with foam or lacking drainage capacity on the wire it will be more satisfactory in the first instance to examine the wet-end critically, bearing in mind the points raised above, to detect and remove sources of aeration.

It is appropriate to mention here that bubbles on the wire of the type which are frequently 'broken' by means of steam jets are not considered to be due directly to aeration, though they are generally accentuated when stock is aerated. The bubbles are too large to originate from air actually in the suspension and come mainly from vortices in the breast box, stock jump on the wire, and accumulations of air in the breast box which become large bubbles and are then emitted from the slice. Air can also get sucked in between the slice and the wire and there are various devices designed to alleviate this.

1B.8 HYDRAULIC DISTURBANCES

Hydraulic disturbances in the main backwater circuit can have a direct effect on the substance of the paper since any fluctuation in pressure which reaches the slice produces a variation in flow rate. Such fluctuations can be conveniently divided into two categories: those caused by a sudden pulse of pressure which produces a surge that eventually reaches the slice, and those caused by a vibration in the system which sets up a wave of continuously oscillating pressure and produces a cycle in substance of the paper of the same frequency. On faster machines these disturbances can show up very clearly in the paper and under certain conditions may be so extreme as to prevent paper being made; it is, therefore, important to be aware of their causes and the remedies available.

1B.8 1 Flow surges

Mardon and his colleagues (40) made a comprehensive investigation of

hydraulic oscillations in the approach system and breast box of a fast machine and measured fluctuations in pressure of a frequency less than one cycle per second; these oscillations were compared with beta-ray traces along the machine and high-speed ciné records of the wire and fluttering of the dry line in order to assess their effect on the paper. Generally the frequency of the vibrations was found to diminish from the mixing pump onwards, though the amplitude increased.

As a result of this work surges in flow with their accompanying oscillations were found to be very dependent on the percentage of free air in the stock, the lower the percentage the less the magnitude of the oscillations. The surges originated where abrupt changes in pressure occurred at the mixing pump, well-throttled valves, tee-branches, etc., where air was able to separate out—a similar type of phenomenon to cavitation but dependent more on instability of the flow than development of a very low static pressure.

Some suppression of these surges was found possible by using perforated orifice plates in the flow system after bends and valves where separation of flow was likely to occur. Also flexible couplings and a tank to absorb the surges immediately in front of the breast box should prove beneficial. The question of using a special surge tank has also been considered by Baines (34) who approached the subject mathematically and concluded that flow surges should be considerably reduced in magnitude provided the natural period of oscillation of the tank were much greater than that of the surge.

1B.8 2 Vibrations in pressure

Apart from oscillations set up due to surges in the flow, vibrations occur in the system which are transmitted as pressure waves in a manner similar to the transmission of sound vibrations in air. The essential difference between the vibrational type of disturbance and the flow surge is that in the former case the pressure can be affected both upstream and downstream, whereas a surge affects only downstream of the source of disturbance. Pressure oscillations of this vibrational type are not affected by air in the stock and originate primarily from mechanical vibrations in the system.

Besides Mardon, several other workers, including Cuffey (30, 70) and Reitzel (42), have investigated this type of oscillation in an endeavour to track down the regular and rapid fluctuations in substance of the paper which are produced as a direct result and which, when severe, are shown up as 'barring' on the wire. Some pressure vibrations are initiated at the mixing pump but according to Mardon these tend to die out as the flow progresses through the system. Vibrating screens are a particularly frequent source of pressure oscillation and if they get into synchronization can be so bad that stock on the wire shows a most prominent barring effect; it may be necessary to take specific steps to prevent this happening by coupling the screens out-of-phase instead of using separate motors. In a similar way the impellers in enclosed screens, at least under certain conditions

and at certain speeds of rotation, can create pressure pulses and in many installations have been found to produce a cyclic pattern of the same frequency in the substance of the paper.

Cuffey has emphasized how difficult it is to trace the source of these vibrations and has found that they can even be transmitted from one machine to another. Forming boards and table rolls may set up a resonance which affects the substance while in some cases the whole breast box and slice lips may vibrate; other sources of vibration which have been observed to affect the substance are the shake and rotating machinery of different types. In association with Ingram (70) Cuffey described one investigation in some detail and it is apparent from this work that the process of elimi-nating vibrations causing flow disturbances is a very complex task. Furthermore there does not appear to be an easy means of easing their severity if the source cannot be traced; according to Baines (34) a surge tank would reduce oscillations of this type, particularly a shallow one with a large area, but this is not a practical structure for most machines and would not prevent vibrations being induced in the breast box itself.

A slightly different approach to the problem of detecting and tracing the source of cyclic variations in substance, caused not only by vibrations but also from other sources, has been developed by the British Paper and Board Research Association. This technique involves the measurement of several variables on the machine and simultaneous recording on a multi-channel galvanometer. High-frequency substance variations beyond the sensitivity of a beta-ray gauge on the machine are measured using a specially-developed instrument which can sense changes in optical density of the web. Subsequent analysis of the different records enables relation-ships between the variables to be examined and, in particular, any cycles occurring can be evaluated and correlated. Apart from its use in isolating the sources of substance oscillations this method is, of course, valuable for general investigations to discover how one part of a system affects another.

RUNNING THE WET-END FLOW SYSTEM

1C.1 DAILY OPERATION

As with all parts of the paper machine, the problem of keeping adequate control on the performance and general efficiency with which the wet-end flow system operates may be considered from two broad aspects. First, it is necessary to look at the question from the standpoint of day-to-day working. What measurements are essential and what measurements can be regarded as important or simply as useful for the machineman to have in order that he can best keep a check on the running conditions; what variables should be controlled whenever possible? Second, the problem of longer-term operation must be dealt with. What maintenance and operational checks appear desirable to ensure that general conditions in the flow system do not alter over a period of time to the detriment of running efficiency?

Each of these aspects will now be considered in detail. The question of substance control, both along and across the machine, is such an important subject that for convenience it will be treated separately. Finally, there is a section dealing with practical aspects of running the wet-end flow system.

1C.1 1 Essential measurements

The formation and general quality of the paper cannot be expected to keep uniform over a period unless the making conditions on the wire are the same. The relation between the wire and the slice jet velocities, together with the quantity of backwater diluting the fresh stuff, are both most important factors in determining the conditions of formation and drainage on the wire, at least on all but very slow paper machines. It is, therefore, essential to have a measure of a property related to the slice jet velocity, preferably the pressure behind the slice, and of the wire speed and the width of opening of the slice, each of which govern these factors.

Pressure behind the slice is conveniently measured from an appropriate water or air-purged tapping, or a diaphragm at the side of the breast box. It is not particularly important that an absolute or even a completely representative value of the pressure is obtained, so long as the measurement follows closely with the overall effective pressure behind the slice. Alternatively, in open breast boxes it is equally satisfactory to use the surface level in the box to give a measure of the head above the slice. Pressure in the box itself will be greater than the pressure head behind the slice but so long as flow rates do not vary considerably for any particular head, i.e. a wide range of slice opening is not used, then the relatively small head difference due to pressure loss in the breast box fittings will not vary significantly.

Wire speed can be measured from a special tachometer on the driving roll or couch. On all machines the speed will be measured at some point, but this is usually either at the main driving section in the cylinders or at the reel-up. The wire speed may be inferred from a measurement off some other part of the machine provided the draw difference does not alter to any extent; on many machines, however, draw differences can vary the equivalent of several per cent. of the machine speed and this will render the measurement too inaccurate to serve for the purpose of comparison with the slice jet speed.

In practice it is the ratio or difference between the slice jet velocity and the wire speed which is important so a precise determination of either figure is unnecessary so long as the measurement bears an accurate and consistent relation to the true value. The presentation of the two appropriate figures to the machineman has already been discussed in 1A.1 5 and it is normally preferable to work in terms of velocities rather than heads, i.e. to transform the slice pressure or head determination into an equivalent velocity (for which the simple conversion formula is adequate). The slice pressure conversion can be performed automatically in the same way in which differential pressure measurements are converted to give a flow reading, and the resulting velocity can be conveniently displayed on a recorder along with the wire velocity. Even more satisfactory, there is no difficulty in obtaining a differential signal to allow the velocity difference or the ratio between the velocities to be shown on a separate digital indicator or recorder (84); this enables the machineman to see at a glance the effect of any unsuspected or deliberate change in operating conditions. The positions of two pens giving a double trace on a single recorder do not show small differences very clearly and use of a differential record in this way will improve the value of the measurements appreciably.

Usually some form of measurement of the width of opening of the slice can be obtained from the lifting mechanism. This is, unfortunately, not usually very satisfactory. Backlash in the mechanical system and alteration of the gap under pressure contribute to reducing the usefulness of what is usually a relatively crude reading anyway. Ideally it would be preferable to measure the opening of the slice lips directly and, if the bottom lip can be assumed rigidly fixed as is usually the case, this effectively means measuring the position of the top lip relative to a fixed datum point by means of a suitable micrometer. It is also useful to have a measure at several points across the slice, even opposite every jackscrew, of the extent to which the slice is being distorted relative to the top lip as a whole. In many ways this latter facility is of greater importance than a single average reading for the slice opening because it assists in attaining cross-web substance uniformity. The basic reason for measuring the average slice opening is to assess the volume flow of stock since, for a given head, this depends entirely on the slice opening. However, as will be mentioned shortly, it is also possible to do this by taking a direct flow measurement in the approach system.

Finally, in the category of essential information can be included several pressure measurements in the system. Gauges are generally adequate for

this purpose and siting depends entirely on the organization of the wet-end. Familiar positions in the approach system will include the mixing pump discharge (this may be a combined pressure/suction gauge when priming is done by application of vacuum) and before and after cleaning equipment; also, of course, pressure gauges will be available on such positions as the discharge side of the spray pump and excess whitewater pump. These gauges are often seen in poor condition, especially where the system is subject to considerable hydraulic vibration and the sensing element is not damped sufficiently; perhaps more than anything else it is the sign of an efficient instrument department and attentive machine crews when they are kept well serviced and regularly checked.

1C.1 2 Important measurements

The measurements listed above are all essential because upon them depends the machineman's ability to set conditions at the wet-end accurately and consistently both during a making and from one making to the next. There are a number of other measurements which assist the machineman to keep a check on the wet-end conditions and these may be loosely divided into important or simply useful in value. Important measurements are of breast box stock volume flow, temperature, pH and the flow in the various chemical and steam supply lines.

The volume flow of stock to the breast box is unfortunately not easily determined and this measurement is rarely seen on a paper machine, though there has been at least one report of its application (33). Yet as a complement to the rough slice opening indication it has considerable potential value. Under particular slice pressure and wire speed conditions (and assuming, of course, that the fresh stuff flow and consistency are adequately regulated), the breast box flow corresponds precisely to the volume of backwater being used for dilution and hence will give both an accurate idea of drainage conditions on the wire and permit the machineman to reproduce previous conditions more exactly. The backwater dilution flow at start-up is frequently set in the first place by comparing the value in previous makings of such things as the power used by the mixing pump, the gate opening in a simple mixing box, and the position of the main throttling valve; afterwards the position of the dry line on the wire and the vacuum on the suction boxes are the main criteria for assessing adjustments to the quantity of dilution water required and it is by no means easy from these alone to ensure that repeatable making conditions are obtained. For one thing the volume of dilution water can be increased considerably (keeping the slice pressure constant), thereby lowering appreciably the consistency of stock in the breast box, yet most of the extra water drains through the wire at the table rolls and the position of the dry-line and suction box vacuum may alter only very slightly. The formation and making conditions on the wire may have altered completely at the lower consistency yet there will be nothing in the general running of the machine at the wet-end to indicate this. Thus, used intelligently, a measurement of the breast box flow would be very helpful.

It is possible to measure this flow adequately by means of differential

pressure readings across a normal orifice plate with filtered water purging of the tappings. When there is fear of the usual concentric orifice clogging, a segmental orifice open only in the bottom half or a flow nozzle can be used. The reading need not be absolutely correct, nor accurately calibrated, so long as it responds with adequate sensitivity to the sort of changes in flow met with in practice. Some pressure loss will occur across an orifice plate or flow nozzle but this would necessitate an important increase in power only if the mixing pump and throttling valve were at all times closely regulated to use as little power as possible (in most cases they are not). A venturi meter has a much lower pressure loss than either an orifice plate or flow nozzle but, particularly for larger machines, would become very large to cope with the flows involved and would need an extremely lengthy straight run of piping. The venturi meter is also said to be more sensitive to viscosity changes though this is more relevant for thick stock. The alternative, though expensive, is to use a magnetic flow meter; it would be more important in this case to ensure that variation in aeration of the stock did not have a significant effect on the reading though the degree of turbulence does not affect this instrument as it may with other types. Whatever the method chosen, to obtain full value a recorder for the flow would be necessary. With the tapered side inlet approach system the over-flow would have to be taken into account and a second flow measurement (shown on the same recorder for convenience) becomes necessary; this adds to the complexity and expense of obtaining satisfactory breast box flow measurement.

The temperature of the stock, measured most conveniently in the pit, is an important reading to have available primarily because of its influence on drainage rate on the wire. It is becoming more and more usual to heat stock, either at the machine or in the preparation system, to obtain the advantage of quicker drainage, and in this event the temperature is of greater importance. It is easy to allow temperatures to get higher because this may make the wire conditions less critical but with higher tempera-tures heat losses are greater and a point must be reached where this procedure, apart from being uncomfortable for working in, becomes uneconomic. Also, at start-up it is important to get the temperature up to normal as quickly as possible. For both these reasons a temperature measurement, shown either on a simple indicator or preferably linked to a recorder, is most useful.

On many machines the heat capacity of the system is sufficiently great for temperatures to remain reasonably steady once equilibrium has been reached. In this case some steam may be applied through closed coils in the main wire or backwater pit at the start-up but not afterwards. How-ever, if steam is in constant use for keeping up the temperature of the wet-end stock, the flow of steam possibly being automatically controlled from the temperature reading, then it is useful in addition to have a measure of the total steam used during any desired period such as a making. A straightforward record of the steam consumed over comparable periods will enable a simple check on seasonal and long-term variations to be kept and, in particular, excessive use of steam will be readily observed.

A knowledge of the pH of the wet-end flow system is important for many reasons that have already been discussed in some detail. In particular, maintaining the pH steady contributes enormously to keeping pitch trouble in bounds. pH may be measured at a number of points in the system, commonly in the main wire or backwater pit, the breast box or strainers, and the reading is normally recorded. For this instrument particularly it is highly important that adequate maintenance is applied to the electrodes, especially when rosin is used in the system as this tends to coat them. Electrodes may need to be cleaned and checked every day or even once a shift if the reading is not to wander significantly.

Associated with a pH meter in the wet-end flow system it is usual to have a liquid alum feed fairly close upstream to the point of pH measurement, possibly in the mixing pump inlet or the backwater pit. This may be the only source of alum in the system or it may be used solely for a final and relatively rapid trimming of the pH. The alum feed is often set manually unless the system has a wide variability, in which case automatic control from the pH recorder may be justified. Either way, it is extremely useful to have a measure of the total quantity of alum used during each making for both operational and accounting purposes, and also possibly to have a record of the alum flow. Alum must of course be provided at a controlled uniform density. Especially when running a low pH the consumption of alum for small reductions in the pH increases rapidly and can rise to phenomenal quantities if careful inspection does not take place at regular intervals. A variable stroke metering pump for delivery of the alum or a rotameter arrangement coupled to a constant flow control are probably the best devices for regulating flow, though care is necessary to avoid blockage of the line. Alternatively a small magnetic flowmeter can be utilized.

Other additives to the wet-end such as wet-strengthening resins, loadings, dyes etc., can be treated in the same way as the alum, and metering pumps, rotameters or flowmeters can be used to advantage for measuring the flow in each of the supply lines and controlling each to a pre-set proportion relative to the fresh-stuff flow. Probably for these additives an indication of the flow with an integrating meter is adequate. Fresh water entering the machine system should be metered, and in this case a recorder is useful for showing up instabilities in the system. The same applies to whitewater effluent for which an integrated reading in conjunction with an average consistency figure (this can be obtained using a special device which samples the flow at regular intervals) is valuable for determination of fibre losses from the flow system.

1C.1 3 Useful measurements

Apart from the more important measurements mentioned above there are three other readings that can provide useful information to help run the wet-end systematically: these are the consistency of the breast box stock, the volume flow of the fresh stuff, and the flows of fresh water or whitewater at points where they may affect the system balance, such as in cleaners, breast box, or wire sprays mixing with the main backwater.

The consistency of the breast box stock has been referred to in some detail and it has been shown that the main backwater circuit settles at an equilibrium consistency which depends essentially on the retention and drainage conditions on the wire. Used preferably in conjunction with a measurement of stock flow to the breast box, this consistency reading would be very helpful for tracing unsuspected disturbances in the system. Any alteration to any of the wet-end conditions—the pH, temperature, loading additions, cleaner reject flow, table roll assembly, forming board position, etc.—may have an effect on drainage conditions, and this would be immediately apparent from a breast box stock consistency record since the consistency will vary with change in any of the wet-end input or output flows or consistencies, or in the retention on the wire.

Though it would require considerable experience to interpret correctly fluctuations in breast box consistency, the author feels confident that an accurate and consistent measurement of this property would be of immeasurable value in trouble-shooting at the wet-end. Unfortunately at the present time no really satisfactory instrument is available which is not sensitive to numerous other changes in conditions. Several approaches are being made similar to those discussed in 1B.21, but the problem with consistencies under 1 per cent. is even greater than for fresh stuff. Other methods such as use of a device for detecting small changes in optical properties have been tried but have so far not met with much success. This is one problem that warrants intensive research and it is to be hoped that a suitable instrument will become available soon. With an on-line computer the breast box consistency can be calculated by means of a material balance based on data from the fresh stuff and excess whitewater flows together with the substance of the paper. This provides an alternative approach which is very useful.

Measurement of the flow of fresh stuff, presumed to be consistency controlled, can be particularly useful for comparison with a continuous record of the substance of the paper. Also it is possible to see whether changes in certain wet-end conditions, e.g. of the backwater dilution flow, can effect the flow of fresh stuff. This flow measurement poses the same sort of problems on a smaller scale as measurement of the breast box stock flow although, being at a relatively high consistency, in this case the magnetic flowmeter is almost certainly the most suitable device. This particular instrument is more likely to be installed when the fresh stuff line runs direct from the stuff chest to the mixing pump; the flow rate will then be automatically controlled and the flowmeter becomes an integral part of the system, not simply a measuring device, and so is easier to justify.

Apart from providing a straightforward record of the fresh stuff flow, the flowmeter permits small alterations to the substance to be made with considerably greater accuracy than can normally be achieved simply by altering the main or by-pass stuff valve position based on experience; substance changes of the same grade of paper should also be made more exactly. Other applications involve use of the flow reading for control purposes and these will be considered in more detail in the next section.

A flow measurement could be applied with some value to the excess

whitewater flow. It is hardly possible to specify this in detail because its location would depend essentially on the machine set-up. There will always be a certain quantity of whitewater flowing out of the system, even if only to drain, and a record of this could be of assistance in characterizing the stability of the machine and in trouble-shooting. As already discussed in some detail, any change in input or output from the wet-end will show up in the excess whitewater flow and even if this is measured simply by recording flow over a weir or flume it could be of great potential service.

Finally, measurement of the flow of all important fresh and whitewater lines is almost as important as incorporating pressure gauges. Indicating rotameter-type instruments can generally be adapted for this purpose and at the usual consistencies of whitewater lines no serious difficulty with longer fibres sticking to the rotameter float should be encountered. Making up or wear of sprays can affect the flow through them considerably, even for the same pressure gauge setting, and when the spray is invisible, as for instance in some closed breast boxes or a suction roll, this can become a source of trouble that is difficult to trace. Small rotameters are also advisable on pump sealing gland lines where a worn gland can admit a surprising quantity of fresh water to the system. If it is not considered necessary to install rotameters on individual fresh water lines at least the total flow of fresh water to wire guide, dandy spray, roll sprays, cutter jets, suction box seals, etc. should be measured or checked at intervals.

1C.1 4 Control applications

There are a number of control applications which can with advantage be installed in the wet-end flow system. By far the most important is the level in the breast box or effective head at the slice but other applications such as control of the fresh stuff flow, pit levels, temperature, pH, etc. will be briefly mentioned.

The level of stock in the breast box or the total head at the slice in an air-loaded box regulates the pressure behind the slice and hence the velocity of the slice jet, so it is vital that there should be as little variation in this as possible. On slower machines the approach system may be sufficiently stable for a straightforward stock flow control valve, once set, to keep the slice head adequately steady. But on faster machines it is generally advisable to control the head. This is done most efficiently by a three-term control on the main flow valve: the integral action is necessary because flow demand or supply pressure changes produce offset in the control operation, i.e. the head is then actually controlled at a value different to that required; the derivative action provides for a rapid reaction to disturbances in the system and reduces the time needed to effect a correction.

Instead of applying control to the main stock flow valve, which becomes very large on fast machines, there are two alternative systems of control that can be used. These are particularly useful in conjunction with an a.c. mixing pump motor when the flexibility of operation provided by a d.c. motor is absent. Firstly, control can be applied to a valve on a relatively

72

small recirculation line round the mixing pump (normally with such an arrangement the recirculation would not return directly to the suction side of the pump but to the backwater pit or silo). With this system the main flow valve opening is rarely altered, indeed a straight-forward air-operated gate valve which is either fully open or closed is sometimes used, and the smaller control valve on the recirculation line provides a more sensitive means of regulating flow to the breast box. The other control system that can be used involves a by-pass line, the main stock pipeline being divided in two, one large branch containing a hand valve and the other smaller branch in parallel containing the control valve. This too has the advantage of providing a more sensitive control on flow to the breast box than a single valve in the main stock line. However, Hasu (81), in an analysis of the performance of these two systems, has shown that the sensitivity of control achieved with a recirculation valve arrangement is much less dependent on the total flow than when control is on a by-pass valve, especially when the pump curve is steep as is usually the case with mixing pumps. The recirculation method thus appears preferable.

It is most important that the position of the flow control valve is recorded, usually on the same chart as the level or slice head, because this trace gives more evidence of what the controller is doing than the near straight line that will probably be drawn for the head measurement when the controller is properly adjusted. With such a controller if the speed of response is adequate it is only necessary at start-up to set the head required to give the desired flow velocity from the slice and this is then reached automatically provided the mixing pump gives sufficient pressure.

In some cases this control of slice head in the breast box is elaborated and the set-point of the controller is arranged to be governed by the speed of the wire (following the theoretical relationship between wire and slice jet velocity). The machineman sets the desired relationship between the wire speed and head at the slice in a similar way to that discussed earlier for manual operation, and the controller then takes care of any changes in wire speed; if the machine is speeded up a rise in head will automatically follow. Eastwood and Gade (31) have described such an application in which a pneumatic speed measurement obtained from the couch shaft is squared and the signal used to set the control point of the breast box level; a small positive or negative bias is set by the machineman and a manual cut-out is available if necessary. The authors state that this arrangement has proved most helpful at start-up by reducing breaks and spoilt paper caused when increasing the speed. However, in the opinion of the author this will normally be unnecessarily elaborate; it cannot be easy to justify such a control solely for speed changes since it is not difficult for the machineman, in the course of making all the other alterations usually necessary, to reset the breast box level control point to suit the new speed according to an appropriate chart or graph. (Even when this operation is done automatically it may be necessary anyway to alter the efflux ratio). It could perhaps be argued that the effect on the substance of machine speed fluctuations due to frequency changes or other disturbances could be reduced by using such a control; however, even if such fluctuations

could be followed quickly enough for their effect to be reduced it would probably be more sensible to try first to eliminate these at source if they are definitely known to be detrimental to the machine operation.

One particular advantage of the head controller is that alterations to the volume of backwater used for dilution can be accomplished in the correct way, i.e. without changing the slice jet velocity. If, for example, it is desired to increase the amount of dilution water, the slice can be slowly opened up. As the gap widens so the head in the breast box will fall but the controller will correct this automatically by opening up the flow control valve to preserve the level. Provided the operation of the slice mechanism does not affect the cross-level (as it so often does), this is the ideal way of regulating the amount of dilution water used on the wire.

The level in the stuff box may only be controlled in the sense that an overflow is provided, though a level controller may in some cases be used to throttle the supply line from the fresh stuff chest and this has the advantage of avoiding an overflow. With either a stuff box feed to the mixing pump or a direct line from the stuff chest it is possible to have a control on the flow of fresh stuff by using a flowmeter to regulate the main valve. Not only should the flow be shown on a recorder but also the position of the stuff control valve. The set-point of this controller would then govern the substance of the paper and allow a fine control. Provision of an interlock to close the stuff valve if the mixing pump stops or the dump valve is opened is an easy but valuable accessory, though a preferable method which avoids unnecessary alteration of the fresh stuff valve is to incorporate a second cut-off valve for this purpose.

Paterson and Hazeldine (41) have described an elaboration of this simple technique of fresh stuff flow control in which a signal from a consistency regulator is used in conjunction with the flowmeter signal to control the stuff valve; small deviations of flow or consistency from the desired set-points are added together to give proportional control of the valve and this to a first order of change effectively controls the product of the flow and consistency, i.e. the flow of fibre to the machine. Even further, a speed signal from the machine sets the datum line for fibre quantity, but in the author's opinion this particular refinement is unnecessary for the same reasons given above with reference to speed control of the slice head. Though the idea behind control of the product of flow and consistency is an obvious one, one would like to know whether in fact the short-term substance fluctuations were less than would be the case with a simple flow controller. Certainly the fibre quantity as determined by this arrangement could not be used as an absolute setting for paper of any given substance and a manual override adjusted from substance tests at the dry-end of the machine is an integral part of the set-up. Bearing in mind the shortcomings of consistency regulators the author considers that this system would require careful evaluation with a continuous substance measurement at the dry-end and it may even be found that the short-term weight keeping has worsened when compared to a straightforward flow control system. An arrangement described by Moore and Walsh (66) in which the flowmeter set-point is adjusted by a consistency regulator signal to achieve constant

fibre flow is open to a similar criticism; in their case the consistency regulator is checked hourly against bone-dry determinations and the set-point altered if necessary, but it could be argued that this will be less effective than altering the set-point from determination of the substance of the paper since, after all, the whole point of the exercise is to help keep the dry weight steady. These ideas will be considered in further detail in 1C.3.

Control of the slice opening from position of the dry-line on the wire has been reported by Tousignant and Madgett (79). In this arrangement the position of the dry-line is detected by measuring the flow of backwater from the suction box situated close to the usual position of the line. Changes in this flow are then used to control small movements of the slice at timed intervals (the breast box head presumably being automatically controlled). Two forms of control have been attempted, a direct one with backwater flow controlling slice opening and a more refined system in which the overall vacuum on the suction boxes is first controlled within limits before making slice adjustments. Such a control is theoretically sound, and in fact achieves automatically the important operation of altering the backwater dilution flow according to drainage rate on the wire which is one of the most important functions of the machineman. But such elaboration would only seem justifiable if the dry-line were to fluctuate appreciably and as this would be symptomatic of considerable variations in stock preparation and wire drainage conditions it should be more profitable to seek these out and correct them. Further, a positive argument against using such a control is that it is liable to upset the flow conditions in the backwater circuit, disturbing equilibrium and substance of the paper to a greater extent than exists naturally. It may well be preferable from the point of view of maintaining overall dry weight stability to permit reasonable fluctuations in dry-line position, requiring the machineman to make only relatively larger, but much less frequent, adjustments to the slice opening when a definite shift in drainage rate has occurred.

Other control applications have already been mentioned in the appropriate place and little more need be said about them. Control of the main pit level by regulating the addition of suction box backwater is a simple task and may be preferable to the customary overflow method when it is desired to keep the consistency of the excess flow as low and as steady as possible. Neither a recorder nor indicator should really be necessary unless evident fluctuations occur that require tracing. The excess whitewater pumped from the machine wet-end to a save-all must be flow-controlled to keep the collecting pit level steady, and this particular flow can with value be recorded, even if only indirectly from flow-control valve movement, in order to show up instabilities in the whole wet-end system. The level of pits receiving broke at the wet and dry ends of the machine can also be controlled; in this case the level is normally governed either by varying the volume of broke recirculating round the extraction pump, or by having a separate large pump which comes into operation only when the level rises above a certain point (as during a break). Consistency of broke leaving the pits is regulated by varying the addition of whitewater.

Temperature of the stock can be controlled from the steam flow to heating coils in the main pit either continuously or just at start-up, and pH in a similar way from the alum flow. Though variation in pH is frequently small enough during normal running to remove the necessity of a controller, it should always be remembered that closer control may make it possible to run the wet-end at a higher pH and thereby reduce alum consumption appreciably. If the upstream pressure varies, addition of other chemicals can also be flow-controlled when necessary and in some cases it may be justifiable to control the flow of such chemicals proportionally to the main flow of fresh stuff. For instance, Van Derveer (68) has described a system in which the addition of loading, colour, and Sveen glue are automatically controlled into the mixing pump inlet from a signal received from a master magnetic flowmeter measuring the total stuff to the machine.

1C.2 MAINTENANCE

Maintenance of the wet-end flow system, so far as the papermaker is concerned, amounts almost entirely to one thing, keeping the system clean. The only mechanical parts which require routine inspection, the mixing pump, valves, breast box equipment, and slice, are primarily of engineering rather than papermaking responsibility though the demarcation line varies from one mill to the next. Setting the slice and checking the condition of the all-important slice lips are definitely the responsibility of the papermaking department, though how often this is done thoroughly, possibly by checking the opening with a taper gauge, depends on how sensitive the cross-machine weight profile is and how frequently the jackscrews are adjusted. Also occasionally the position of the lower slice lip relative to the wire should be checked for evenness across the machine in order to show up any long-term deflection or wear of the lip and breast roll.

Regarding cleaning it is only possible to say that each week all pipework, boxes, pits, etc. should be thoroughly hosed down with high-pressure jets; in addition, periodically the whole system will require a thorough clean-out using heated water to which caustic soda or a chemical compound specially designed for the purpose is added. The frequency with which this is done depends entirely on mill conditions and, in particular, on the water used. When scale formation occurs it is often difficult to remove chemically without affecting some metal parts and if wires become coated scouring with acid shortens their life; thorough and regular cleaning with high-pressure jets is very important in such conditions.

Apart from general cleaning there are two related subjects which may conveniently be treated under the heading of maintenance though they have just as much relevance to day-to-day operation. These are the prevention of slime and pitch formation.

1C.2 1 Prevention of slime

In many mills, particularly those using groundwood or waste paper, keeping down accumulations of slime in the system can be quite a problem.

The most common treatment is to add shock dosages of a slimicide, usually an organomercurial such as phenyl mercuric acetate and ethyl mercuric phosphate, or a chlorinated phenol such as phenylphenol, pentachlorophenol and their salts. The quantity added to the system and frequency of dose depends usually on the recommendations of the manufacturer and may be quite an expensive business.

The value of these slimicides has always been hotly debated and it is only comparatively recently that any reliable evidence has become available. The most painstaking examination of this problem has been given in a book by Rathman and reviewed by Russell (73). In carefully controlled experiments extending over a period of eight years Rathman obtained no evidence at all that the use of disinfectants gave a demonstrable improvement in the slime situation; in a mill in which he worked neither the degree of infection nor the number of breaks caused by slime decreased with greater dosages. The effect of a slimicide was only apparent while an effective concentration remained in the system and in practice the concentration from a shock dose diminished so rapidly that the number of organisms was rapidly restored. Rathman concluded that it would be too costly to maintain an effective dose and that shock-dosing has little to commend it.

Another interesting fact that emerged from this work was that seasonal variations in temperature of the system were shown to cause a statistically significant effect on the degree of infection. The degree of infection appeared to rise with increases of temperature of the backwater up to a temperature of about 65 deg. C., above which it began to fall. However, Rathman emphasized the difficulty of isolating a phenomenon of this sort using spot checks and it would not be easy for a mill to study the effects of different conditions on the slime in the system; even so when this is a serious problem it may warrant the making of careful observations, possibly with specially designed containers with which the growth of slime can be more accurately assessed.

Slime forms in the presence of air when bacteria and fungi in the system grow on fibre and alumina debris collected in such places as the stock surface level in boxes, particularly when they are made of wood or concrete. It is probably worsened when the air content of the stock is high and certainly deaerated stock helps considerably to prevent slime becoming troublesome on the machine because fibre is then less likely to adhere to the slime already deposited. Long fibres, loadings and sticky pitch constituents all worsen the slime situation by speeding up growth of the accretion, and corrosion is more rapid where slime is deposited.

The most effective method of preventing slime is undoubtedly good housekeeping. Efficient wash-ups and the pumping round of hot alkali, possibly with a slimicide added, will remove existing slime deposits and prevent a slime growth over the shut period which may break away when the machine is started again. If this needs to be done more frequently than the machine is normally shut the system should be arranged so that cleaning is possible throughout the wet-end, including the stuff box and stuff pipe system, without drawing water from the machine chest. The suction box and whitewater pipes on all machines are particularly liable to slime growth

and special provision may be necessary to keep this part of the system adequately clean.

1C.2 2 Prevention of pitch

The effects of pitch on the paper machine have much in common with those of slime and it is often difficult with small dispersed deposits on the wire to tell the difference between the two without a simple laboratory check. As in the case of slime, when deposited earlier in the stock system pitch is liable to break away in lumps causing holes and breaks in the paper. In addition pitch is more liable to affect the presses and the wire part of the machine. On the presses pitch gathers under the doctor blades and may break away in lumps and affect the sheet; on the wire it gradually reduces drainage, producing light spots in the paper, and may also collect on the dandy, table rolls, forming boards, and suction boxes (on the latter it can accumulate sufficiently to raise the wire and cause loss of vacuum).

Although pulps can be checked in various ways for their propensity to deposit pitch, there are other sources of pitch-like substances in the mill and in the long run the only reliable information comes from keeping accurate records of its occurrence on the machine. Deposition of pitch is affected by the pH and temperature of the backwater and especially in a closed system careful control of these helps to keep the free pitch particles dispersed and encourage their precipitation onto fibres; this reduces the tendency towards agglomeration of the particles in the system where a slight disturbance to the fine state of equilibrium could lead to a sudden heavy deposition. Often opening up the whitewater system slightly appears to help the situation by making the equilibrium less sensitive and reducing the concentration in the system.

Attempts are sometimes made to control pitch by additions of loadings such as diatomaceous earth and hydrous magnesium silicates, which provide a suitable surface on to which the pitch particles may deposit, and also by using calgon and detergents to act as dispersing agents to maintain the pitch in a colloidal state. But apart from other disadvantages these methods are often rather expensive for continual use though, undoubtedly, some improvement can be obtained. There are also mechanical methods of pitch removal including a series of metal baffles placed in the thick stuff after beating when the dissolved pitch content is greatest. Unfortunately, however, this whole problem is far from being satisfactorily solved and in every mill the appearance of pitch on the machine is greeted with much anxiety.

1C.2 3 Long-term records

The importance of obtaining long-term records to act as standards with which to compare conditions during trouble-shooting or when making a deliberate alteration to the machine is fully discussed in Part VI; this procedure is especially important for the wet-end flow system. During normal runs of one or more of the major grades of paper produced on the

machine, when equilibrium has been reasonably established the whole system should be carefully analyzed in addition to noting the readings of all measurements already displayed on the machine. Flows, consistencies, loading content, fibre classification tests, strength and porosity measurements on standard handsheets, and also air content determinations should be performed on samples taken at all the main points including the backwater pit, fresh stuff, cleaner and screen rejects, breast box stock, suction box backwater, and whitewater excess. In addition, any of the properties already discussed which are not measured on a routine or continuous basis, such as the slice opening, pH, temperature, alum and other chemical addition rate, etc., should be checked.

The measurement of flows at the wet-end depends essentially on the accessibility and quantity involved. Smaller flows up to 30 or 40 gallons per minute are conveniently measured, either by the simple bucket and stop watch or with a portable container coupled to a rotameter (the latter is more suitable where short-term variation in flow occurs and is less influenced by the operator, but normally requires more room). Enclosed flows can often be determined with reasonable accuracy by introduction of a concentrated salt solution at a known steady rate and measurement of the diluted concentration in samples drawn downstream; some care is required in general technique and the method of chemical titration, however, especially when the flow is part of a closed circuit. But it is not usually possible to determine all the flows, particularly those for the fresh stuff, the main backwater circuit, and the whitewater excess flow, when special provision has not been made.

Comparing consistency results for the input of fresh stuff and backwater with the output from the mixing pump or box normally enables the main large flows to be assessed with fair accuracy. At least one flow must be known for this method to be applied and the fresh stuff is usually the one most easily measured. If no flow determination is possible then one must be calculated; this may be either the breast box flow determined from the slice pressure and opening (made as accurate as possible by using the exact formulae quoted earlier) or the fresh stuff flow determined from the bone-dry production, fresh stuff consistency and estimates of the loss of fibre at cleaners and in excess whitewater. Both calculations have their limitations and agreement of the main flows calculated in the two ways depends essentially on how representative and accurate are the various measurements; it should, however, be possible to get well within 5 per cent.

Comparison (by determining ash contents of consistency pads) of loading input and output at the same points provides a cross-check on the reliability of the calculations and again agreement should be possible to within 5 per cent.; in a relatively stable system it is also quite possible, with careful sampling and analysis, to obtain agreement in the quantity of long or short fibres entering and leaving the mixing pump to within about 10 per cent. by weight of the total fibre, despite the relative lack of precision of devices like the Bauer McNett Classifier.

The Sankey diagram is a useful device for illustrating the flows of water, fibre or loading throughout the system, but it is only really suitable for

general purposes of comparison with other machines or to examine the outcome of altering the system. For comparison of conditions on the same machine running the same grade of paper but taken on different occasions the Sankey diagram is not sufficiently precise. It is preferable for characterizing the backwater circuit to relate the slice opening with breast box consistency and loading content on a graph and also to calculate the retention of fibre and loading on the wire.

Measurements across the machine of the precise position of the slice lips with regard to each other and to the breast roll are important for their influence on formation and drainage on the wire. Tests for freeness, etc., and possibly also quality checks on handsheets made from the fresh stuff will, of course, be useful, though it is presumed that the establishment of long-term records extends to the preparation process and this information will be more relevant to that section.

1C.3 CONTROL OF SUBSTANCE

The substance of paper is the most important single property and one of the main concerns of the machineman is to ensure that it is correct. Fluctuations in the substance from one roll to the next and within a roll must be reduced to a minimum, and at the same time the substance at different points across the sheet must be uniform. Since the wet-end flow system and, in particular, the flow of fresh stuff to the machine is responsible for determining the substance of the paper, it is appropriate to consider this question now in some detail.

1C.3 1 General comments

The problem of maintaining correct substance is intimately tied up with that of keeping the correct percentage of moisture in the sheet. The substance of paper is defined as the basis weight in the standard humidified atmosphere; thus if a 100 gram per sq. metre paper has an equilibrium moisture content of 10 per cent. but comes off the paper machine at 6 per cent., then the making weight should, strictly speaking, be 96 g.s.m. The difficulty, of course, is that both the humidified moisture content and that of the paper at the reel-up varies, so the actual making weight to be aimed at differs continually. Ideally the dry weight of the paper should be the standard and differences in humidified moisture content averaged and kept as small as possible by making a product of consistent structure; in the example above, for instance, the making weight would be 90 g.s.m. bone-dry.

The traditional method of determining the substance at the reel-up is to tear off a number of layers, trim the edges with a template and weigh on a quadrant balance with a suitably calibrated scale. The shortcomings of this operation are fairly obvious and the main limitation is, of course, that the result of weighing a single sample, or at best the average of two or more samples across the sheet, is taken as representative of the whole roll though it is in fact only a minute part of that roll that happens

to have been made just before the roll reached maximum size. The problem of differing degrees of moisture in the paper as made on the roll is partly overcome by accident, since in the interval between extracting the sample and weighing the paper, moisture is gained or, in a very few cases, lost as the moisture level approaches equilibrium with the atmosphere. This process occurs very rapidly (a sample of newsprint at 6 per cent. moisture rises to 7 per cent. in less than a minute and will be within 0·5 per cent. moisture of the final equilibrium value of between 9 per cent. and 10 per cent. after only 10 minutes or so). Also the rate of change is more rapid the greater the initial difference from the final equilibrium moisture; hence a considerable degree of equalization of moisture naturally occurs before testing. Unfortunately, however, the equilibrium moisture of the paper varies with humidity and temperature of the atmosphere and the conditions in the machine house or in a laboratory close by where the weighing has to be accomplished with reasonable speed may be very different from the standard (65 per cent. humidity, 20 deg. C.).

Normally, however, these limitations to sample weighings rarely seem to cause much concern, but the main reason is probably that standards of uniformity and accuracy are relatively low. With a growing consciousness of the advantages to be gained from keeping a tighter control on the substance, the lower margin of allowance necessary to be within specification and the increased uniformity of other paper properties which occurs when the substance is more uniform, it has become more important to improve methods of substance control. The application of quality control has been encouraged in post-war years and undoubtedly much improvement occurs when such schemes are introduced because they serve to draw attention to the importance of keeping the substance, and for that matter other properties, closer to standard; in practice, an improvement probably occurs more often than not because the machineman is encouraged to leave the process alone more and, in particular, to adjust the stuff valve less frequently.

· The degree of success with which the substance is regulated depends in large measure on the sensitivity of the stuff valve. Unfortunately it is usually impossible to calibrate the average valve satisfactorily because the relatively small alterations in flow required for adequate control of the substance are lost in the backlash of the valve movement. A valve positioner is helpful but this degree of elaboration will normally be thought of only in connection with some form of automatic control from a beta-ray gauge. An alternative which can work very successfully is to utilize a small parallel flow of fresh stuff additional to the main one which is then only altered for large substance changes; this parallel flow can be altered visually in a mixing box system or by a suitably calibrated valve regulating a separate stuff line which goes either to the mixing pump or, preferably and more easily, to the inlet of the pump in the main pit.

1C.3 2 Continuous measurement of the substance

The lack of knowledge of what is happening to the substance in the middle of a roll, except for what the experienced machineman can assess very

approximately from visual evidence of changes in the suction box vacuum and draws, makes some form of on-machine continuous measurement of tremendous importance. The beta ray gauge has succeeded in filling this gap and despite the earlier limitations and inaccuracies of the technique much development work has enabled the electronic stability and sensitivity of the instrument to be greatly increased. For recording changes in substance of the paper over a short period the beta-ray gauge is now extremely valuable, though for long-term regulation of the substance certain precautions in its use are necessary.

In the first place it is important to realize that a really exact measurement of the substance, in the strictly defined sense of the term, is virtually impossible. Even when inaccuracies in the instrument reading due to temperature variation in the air gap, static electricity, different scattering coefficients produced by a change in formation or in the pass-line of the sheet between the source and ionization chamber, and several other minor factors are eliminated or allowed for, the reading is still of paper in a variable state different from what it will stabilize at in standard atmospheric conditions. The paper is stretched, so the area presented for measurement contains less fibre than a sheet of corresponding area drawn from the roll. But more important, as the moisture content on the machine varies, so will the apparent substance, and in contrast to off-machine measurement by sampling there is in this case no equalization effect. This latter basic limitation of the beta-ray gauge is satisfactorily removed only if the instrument is used in conjunction with a moisture meter; in this case a measure of the dry weight of the sheet becomes available and this will be far more valuable for correct adjustment of the stuff valve.

Apart from the limitations imposed by the inferential nature of the instrument reading and the condition of the paper, the fixed beta-ray gauge measures only a portion of the width of the paper web so that another effect must be considered, that of variation across the sheet. This subject will be treated in more detail in 1C.3 4, but the point of importance here is that if the reading is obtained from only one position across the web there must be the possibility of a bias in comparison with the average substance of the sheet unless the substance profile is exceptionally well controlled. This can be overcome to some extent by using a moving beta-ray gauge to give integrated readings taken from a series of rapid cross-web traverses, but this procedure loses the advantage of continuity of record in the machine direction which is so valuable an asset of the gauge. Opinions differ over the best way of countering these difficulties and the solution depends partly on the relative variability along and across the web, and partly on the particular requirements and speed of the machine. When the cross-web substance and moisture profile remains reasonably stable over a long period, possibly the simplest effective method of overall control would require continuous substance measurement on one portion of the web, punctuated at intervals by a traverse to check the cross-web substance level.

It does seem essential, however, that the zero-deviation position of the beta-ray gauge reading used for setting the required running substance for

any particular grade of paper, while being based initially on a test calibra-
tion or data from previous runs, should also be adjusted during the making
to match results obtained from some direct standardized weighing of
the paper. In other words a fundamental comparison should be available
to permit detection of any long-term drift or bias in the beta-ray reading;
this standard may, for instance, be a quickly humidified test weighing done
at intervals on a large sample and compared to the gauge reading at the
time of extraction, or it may be a direct comparison of yardage and weight
of jumbo roll or a slit reel compared to an integrated reading taken over
the appropriate interval. The basis of comparison does not matter so long
as the determination can be done with sufficient accuracy to serve the
purpose of standardizing the beta-ray gauge; suitable statistically deter-
mined error limits would be provided to indicate when action is necessary,
though the equipment may well prove sufficiently accurate and reliable
for the procedure eventually to become redundant.

1C.3 3 Automatic control with a beta-ray gauge

Several attempts to control substance automatically from a beta-ray gauge
on the machine have been reported (7, 9, 18, 28), but the case most fully
documented has been given by Attwood (60). The primary difficulty in
regulating the stuff valve from the beta-ray gauge reading is the long time
lag involved before the effect of an alteration is observed. Continuous
process control with a long time lag is not very satisfactory and Attwood's
method of overcoming this difficulty was to integrate the reading for a
period of $1\frac{1}{2}$ minutes, compare this with a standard to initiate action, then
pause for $2\frac{1}{2}$ minutes giving time for the effect to be registered at the dry-
end before repeating the cycle. Allowance was made for inaccuracies and
random variation in the system by requiring the integrated reading to
be outside a dead zone before action was initiated. Movement of the valve,
which was fitted for accurate adjustment with a special design of positioner,
was made proportional to the deviation outside the dead zone. This
procedure apparently proved very effective and, though it could be further
refined in several ways especially in association with on-line computer
control, illustrates the basic approach for a discontinuous form of control
that overcomes the long time-lag.

Several other ideas have been tried with the same objective of endeavour-
ing to overcome the time-lag. One is that the speed of the machine is altered
instead of the stuff valve to correct the substance of the paper. This is fre-
quently easier to arrange than alteration of the stuff valve and will make
the response quicker and possibly finer; it is, however, practicable only
for very small corrections on slower machines because otherwise the power
required to continually accelerate and decelerate the machine is in danger
of becoming excessive. In addition objections can be raised that with
this sort of control the machine cannot be run at the maximum possible
economic speed all the time and if the degree of correction were at all
high, say above 1 per cent. or 2 per cent., then the relative change in slice

jet speed and wire speed might affect formation and other conditions on the machine may be upset.

It has also been proposed that the substance should be controlled from a beta-ray gauge reading at the presses, or possibly even from the suction box vacuum. Both of these measurements would be affected by varying water content of the sheet and, in the case of the latter, by the porosity of the sheet, but the set-point of the control in either case would come from a beta-ray gauge reading at the dry-end. The idea is that faster fluctuations in the substance are removed by the more rapid response gained from situating the measuring point at the wet-end, while over the long-term the substance of the paper is controlled from the dry-end. An alternative arrangement is to measure both substance and moisture at the presses, for which a non-contacting type of moisture meter is needed, and compute the dry weight of the paper from these two measurements.

Though these schemes sound plausible in theory they have several unattractive features and may well prove awkward to manage successfully. Apart from the practical difficulties of using electronic equipment at the wet-end and the uncertainty of how much other factors will influence the efficiency of control, the gain in response time may not be very large because on many machines it can take longer for fibre to travel from the stuff valve to the suction boxes or presses, than from the press to the dry-end. In this event the reduction in time-lag would hardly be great enough to warrant the added complexity of instrumentation and it is probably only on board or heavy-substance machines that the additional time required for the sheet to travel between the presses and reel-up can usefully be eliminated.

In the author's opinion the time-lag between the correcting signal to the stuff valve and detection at the beta-ray gauge need not anyway present a difficulty provided the control is not expected to cope with rapid disturbances. Variation in the flow of fresh fibre to the machine is after all the main source of longer-term variation in substance, at least of a permanent nature as opposed to the transient changes discussed in 1A.2, so it is logical for this to be the control point. Provided adequate control of conditions is exercised in the preparation plant, and the flow and consistency of the fresh stuff is regulated as closely as possible, then a beta-ray gauge controlling the stuff valve should be able to smooth out variations of the order of several minutes very successfully. This presumes, as stressed earlier, that there is an appropriate standard to which the gauge reading can, if necessary, be compared at intervals, and also that moisture in the paper is either measured simultaneously and allowed for or is adequately controlled and therefore assumed to be sufficiently constant. Even then a wise precaution is to provide means to attract the attention of the operators when the automatic control adjusts the stuff valve beyond certain set limits, in order to prevent the substance going haywire in the event of a breakdown in the system. More rapid oscillations and fluctuations with periods of up to two or three minutes due to vibrations and speed variations in the drive could not possibly be corrected by this sort of control and must be tackled at source.

1C.3 4 Control of substance across the sheet

Setting the substance uniformly across the machine is extremely important because any position which is heavier will also reach the dry-end containing more moisture and the combined effect of this is to produce a damp place in the roll. Apart from this a heavy streak may have experienced different drying stresses from the rest of the web and will receive a different finish at the calenders; in extreme cases excessive moisture at the calenders may cause blackening of the paper in a heavy streak and the web may crease and break. All these effects are detrimental to uniformity of product across the web and with thicker papers cut into sheets uneven basis weight also produces cockling. Any defect in the approach flow system, breast box design and equipment, or slice setting can cause unevenness, but apart from this the machineman may deliberately run one position different in dry weight from the rest of the web to remedy trouble on the wire, presses, or in the drying section. A ridge in the wire giving poor drainage may necessitate running lighter in that position, as may a deficiency in a wet or dry felt which impedes water removal. The edges of the sheet, particularly the front side away from the drive gears which obstruct ingoing air flow on a machine with an open drying section, may be run heavier to counteract the tendency to become overdry. In all cases, however, when the substance is uneven across the web for any length of time trouble is likely to occur sooner or later. For example, a heavy streak will wear and plug a new press felt faster because of the greater quantity of water extracted, so that as the felt ages it is less able to cope with the water and the presence of the streak becomes more apparent.

Particularly with faster machines, it is of paramount importance that a level roll is produced otherwise it will be very difficult for the roll to be slit satisfactorily. In their endeavours to achieve this machine crews will often adjust the substance to overcome deficiencies of drying or calendering. This is thoroughly bad practice and can only be condoned as an essentially provisional and temporary expedient. The most satisfactory approach in the long run is to set the substance as evenly as possible, then correct for any deficiencies in moisture profile (this pre-supposes ideally a means of correcting moisture unevenness at any position across the web apart from altering press load to overcome a general tendency to be damper or drier in the middle compared to the edges of the roll). Finally the air blowers on the calenders can help to even up paper thickness across the roll.

There are many methods by which an attempt is made to control the substance across the machine from samples extracted from finished rolls, but the difficulty of moisture pick-up is even harder to overcome in this case because of the time which will be required to complete the testing. Weighing small squares of the paper is particularly prone to this error unless sufficient time is allowed before testing for all the strips to reach approximate moisture equilibrium. The off-machine beta-ray profiler provides a very useful continuous cross-web substance curve from a strip, or preferably a number of strips taken together, and can be quicker and therefore less likely to be subject to moisture variation. When suitably

4   85

determined control lines are drawn on the profile curves and the position of jack-screws is marked, the machineman can easily interpret the result and set the substance across the sheet more evenly than in any other way. The main difficulty with this method, as with others dependent on testing a strip taken from the machine roll, is the time and energy involved in performing the operation; if the machineman is to adjust the jack-screws conscientiously, then check on the adjustment, and do this as often as is necessary to get the substance across the sheet as level as possible, a great deal of work will be required. Furthermore, the occasions when the greatest change in the cross-web profile is likely to occur, and when checking the substance across the sheet can be most useful, are at start-up and during alterations in substance, speed, and breast-box flow conditions; unfortunately, it is at precisely these occasions that crews and laboratory testing personnel are busiest and requests for a series of profiles may not be well received.

For a machine with a very stable cross-substance profile which hardly alters from one shift to the next this may nevertheless be an adequate arrangement. An on-machine beta-ray gauge capable of traversing across the web will perform the same job more easily though ultimately, especially for faster machines, the combined beta-ray gauge and moisture meter traversing across the machine at the reel-up is coming into more general use. This instrument has the supreme advantage that the true dry-fibre weight curve across the machine can be exhibited in an appropriate form and with it the moisture profile and also, possibly, the total substance profile (though if the moisture profile is adequately controlled, perhaps automatically, the dry-fibre weight becomes superfluous). The machineman should then succeed in adjusting the jack-screws far more efficiently, particularly when adjustments can be made on the basis of a number of such profiles obtained at suitable intervals and preferably displayed one above the other on an XY recorder; persistent heavy or light peaks can be distinguished more accurately from the random fluctuations which must exist in any single cross machine profile. Because of the time involved in making each traverse some machine-direction variation must be included in the profile drawn by any on-machine substance measuring device; however, provided action is taken from visual examination of a number of such profiles the fluctuations from this cause will be averaged out. In exceptional cases it would be perfectly feasible to reduce the average cross-web variation below that of the machine-direction to an extent dependent on the traversing speed and relative degree of fluctuation in the two directions, i.e. on the general stability and characteristics of the system. The effect of alteration to the jack-screws, or of the whole slice, cleaning the slice lips, adjustment of flow at the deckles, etc., can also be quickly displayed using this technique so that accurate adjustment and correction becomes much easier.

There have been one or two reports of the use of traversing beta-ray gauges (18, 28, 56, 86) in which details of the traversing speeds, their use for machine direction substance control, and other general points are given, but as yet it is not easy to generalize on details. The author believes that

after initial adjustment it should not be necessary on most machines to traverse the sheet more frequently than about twice an hour though the machineman should, of course, be able to obtain a profile at any time when he requires one; if considerable cross-substance variation can occur in the sheet at a quicker rate than this then the approach flow and breast box system is likely to be relatively unstable and rather than trying to chase the cross-machine substance fluctuations it would be more satisfactory to go to the root of the trouble. With this frequency of traverse the same instrument could, as mentioned above, satisfactorily be used for providing a machine direction record, possibly with automatic control, provided the reading were locked for the short duration necessary to make a traverse.

1C.4 PRACTICAL POINTS

The wet-end system of a paper machine, probably more than any other part, is individual to the machine. For that reason a discussion of practical aspects, as opposed to general principles, is of limited value. Even so there are several points which seem worth noting and these are dealt with below.

1C.4 1 General considerations affecting start-up conditions

The ability displayed by a machineman when getting his machine going after a shut period is put very high in assessment of his overall merit and skill. The machineman is well aware of this and also, of course, realises that it is only too easy to compare his time to get the sheet through to the reel-up with that of his colleagues on the other shifts. The result of this is seen all too often in paper mills; paper is made at the reel-up in good time, only to be torn up for hours afterwards because it is inferior in quality.

The fault does not lie entirely with the machineman for often the beaterman, in his haste to fill the machine chests, skimps treatment in the beater or hydrapulper and is not so particular about the results of routine laboratory tests on the stuff. Nevertheless, each beaterman and machineman has his own routine for starting a machine and it would be an unwise person who attempted to interfere with this unnecessarily. A routine is gradually worked out between them which, provided they are reasonably capable and do not work in competition with or isolation from one another, reaches a point where it is at least adequate for starting the machine in reasonable time.

The trouble always comes when the stock is run on the wire and attempts are made to get the web through the presses and drying section; one Monday morning everything will go smoothly, next time there are breaks galore at the couch and everywhere else on the machine, and even when a reel has been built up without too many breaks it is only useful for broke because of the poor quality. Some blame can no doubt be attached to variations in pulp quality yet on most machines, when everything is running smoothly, surprisingly wide swings in pulp preparation can be tolerated without ruining the paper quality or producing an excessive number of

breaks. Also, perhaps more frequently than is necessary in many mills, conditions are not set ready for the particular paper to be made as well as they might be. This, of course, applies to the whole machine and it goes without saying that all machine crews should know, from records of previous operation they keep either on paper or mentally, precisely where to position the stuff valve, slice, presses, draws, etc. to ensure they will be close to the eventual settings required. Apart from such more obvious faults, however, it is frequently the case that inadequate preparation is made to start up as close to normal running condition as possible.

In older fine paper mills where treatment in beaters is a lengthy process stuff will be kept stored in the preparation system up to and including the machine chest, at least provided the shut is not longer than a normal week-end. In such systems, particularly when recirculation is confined to a simple backwater system with no hog-pit and with fresh water in general use elsewhere, the normal running condition on the machine is rapidly achieved with regard to fines recirculation; the time for establishment of equilibrium in the main backwater circuit has already been discussed in 1A.2 5. In fact, with frequent colour changes and quality changes, the efficiency of operation of such a machine hinges very much on being able to settle down rapidly to the usual speed and general running conditions.

Contrast this with the position of a modern fast machine where it is customary to run out the chest and empty the system for a clean-up. If at the start-up fresh water is used until the whitewater system commences to operate, then the whole character of the preparation system will change over a period lasting many hours. At worst this might simply necessitate frequent alterations to the flow of backwater used for diluting the fresh stuff to take care of fluctuations in wetness on the wire, and also changes to the stuff valve to keep the substance correct. But with increasing recirculation and build-up of fines in the whitewater system it is probable that refining will require alteration as well and it may well prove difficult to keep the paper quality consistent over this period. To alleviate this it would, where no colour changes are involved, be well worth retaining the whitewater tank full over a normal shut period, even if this incurred the problem of slime build-up and necessitated use of a small agitator at start-up or, possibly, during the whole shut period. By this means it should be possible to reduce considerably the fresh water usage at start-up and ensure a quicker approach in the preparation stage to normal running.

It is often the case with faster machines making newsprint, tissue, and kraft papers that the quality is likely to suffer if insufficient broke is available. This presents a similar problem to the fines in whitewater but cannot be solved so easily as few mills regularly like to keep broke tanks full over a normal week-end period. On such machines it is general to have hog pits collecting the sheet washed off the wire so considerable broke is usually generated right at the start; this, if returned with a minimum of treatment straight to a broke chest and thence to the machine chest, will greatly assist in establishing equilibrium reasonably quickly so far as broke characteristics are concerned. It is, though, probably more satisfactory to use a dry-end hydrapulper or broke pulper to break down trim or reels

stripped from the previous week and ensure that this is done early enough to permit the usual supply of broke to be available for metering in at the addition point.

On all machines a more familiar start-up problem is to obtain normal running conditions with regard to temperature and chemical condition of the stock, especially pH. On larger machines it may take many hours to reach the usual running temperature and pH and this all adds to the problem of keeping conditions and quality consistent. In particular, it usually necessitates starting up at a slower speed than normal and it may take two or three shifts before speed is finally got up. During all this time the machine crews have to keep extremely alert to ensure that everything is kept under control and it is not surprising that the general quality of paper made during this period, if not actually broke, is of lower standard or differs in some important respect from the usual quality.

With regard to temperature the remedy at first sight seems simple. Steam condensing pipes in the machine backwater pit will enable normal running temperature to be attained at start-up, while adequate supply of heat to the preparation plant should likewise ensure that the fresh stuff is not so cold as to affect adversely the stock temperature at the most critical point, the breast box. Unfortunately it is precisely at this time that steam demand in the whole mill is highest with the drying cylinders usually drawing as much steam as it is possible to get hold of. Even so the situation may well be worth examining in many mills where temperature is known to be a major factor in requiring a slow start-up in machine speed. By appropriate metering of steam and more careful setting of valves it may be practicable to achieve a better compromise than the existing one.

The same difficulty should not apply to alum supply whether by batch in powdered form or from a central liquid supply plant. On machines where the procedure is to use alum in the beaters with perhaps only a trimming device on the machine itself, the problem of pH fluctuations at start-up is not likely with adequate control to be serious. But when the sole alum control is in the machine backwater pit it may be difficult at first to keep pace with the variations when the machine starts. A pH recorder and controller is invaluable for this but even then it may be more satisfactory to add alum temporarily in the preparation plant, especially when fresh water is used at start-up. The method adopted must, of course, depend on the lay-out but it is well worth considering dosing the white-water tank itself when this is first filled with fresh water for use in diluting the various parts of the preparation system.

1C.42 Start-up of the machine

The first step on any machine is to fill the machine backwater pit with fresh water and begin flushing out the system through the mixing box or pump, cleaners, screens and breast box. This water may at first go to drain but eventually it can be passed through a dump valve back to the back-water pit to be recirculated round for some time. On some machines,

depending on the lay-out, the water will pass through the slice and onto the wire and this is necessary eventually anyway if the slice is to be cleaned; the wire may be crawled round and washed off while this is being done or it may be stationary with the debris collecting on the wire to be washed off at intervals. When necessary, the temperature of the water will be gradually raised during this time and circulation will help to heat up the whole system. With high temperatures care is necessary to avoid damaging the wire, especially if the sprays are cold at first. Raising the temperature to near normal running is advantageous not only from the point of view of drainage of the stock but also for the slice lips which may expand to nearer their eventual shape and will not then be liable to affect the cross-level substance after start-up.

By the time the machine is ready to start the pH of the water should also have been regulated to an appropriate value. Screen and wire sprays, perforated roll drive and seals, shake, breast box air-loading compressor, hog-pit agitator, vacuum pumps, broke pump, etc. are all started and checked. Then the machine chest pump is started and, in the absence of an automatic control, the throttling valve is manually adjusted to set a small overflow from the stuff box once the box has filled. In the meantime the mixing pump speed and the main valve governing the flow of backwater should have been set manually or automatically to give approximately a head at the slice appropriate to the starting-up speed of the wire. The stuff valve or gate is slowly opened and the dry-line and vacuum gauge on the suction boxes (which should be visible from the valve) are carefully watched; with enclosed systems, it is advantageous to have a separate stuff cut-off valve apart from the substance regulating valve for this purpose so that the latter need not be subjected to violent movement from its normal working position.

Until the backwater consistency has built up to near normal in three or four circuits the substance will be very light and sometimes an attempt is made to compensate for this by opening the stuff valve wider for a short period. There is, however, little point in rushing this part of the procedure and the necessary delay can be usefully devoted to many tasks. Amongst these may be mentioned setting of the dry-line evenly by adjusting the jack-screws (which should reduce the alteration necessary once the substance across the web has been checked at the dry-end), ensuring the head is up for the wire speed (particularly if the stock is cold and drainage slower at start-up there may be a tendency to run with the head too low and the poor formation resulting can produce trouble when feeding through the presses and drying section), setting the edges as well as possible (particularly important when there is little or no trim), and general inspection of the wire part which is dealt with in detail in Part 3.

When sufficient whitewater is available those sprays normally using whitewater will be turned over from fresh water. By the time the vacuum on the suction boxes and couch is adjusted, the dandy lowered if required, and weight is applied to the jacketed couch roll or the presser roll lowered to normal running position, conditions in the backwater circuit should be close to equilibrium. With the stuff valve checked back if necessary to its

usual setting the sheet on the wire will then be ready for passing through to the presses.

On modern machines it is becoming customary to ease the task of the machineman at start-up and speed the procedure by grouping the various switches and controls in convenient positions which allow him to keep a continual eye on the situation; it is surprising how much dashing about the average machineman has to do on an older machine when he should have ample time to watch and adjust the more important and vulnerable aspects of the wire part. The logical conclusions of the process of grouping is to have a single control panel at the wet-end with the starting buttons placed in a suitable sequence. Such an arrangement has been described in some detail by Eastwood and Cade (31) with a complete start-up sequence of operations included, from turning on fresh water to the showers and closing the wire pit drain valve right through to opening of the stuff valve. One advantage of this is that safeguards are easily built into the sequence to ensure, for example, that steam heating is not allowed into the pit before an adequate level of water has been reached. Eastwood and Gade also describe two further refinements, the use of a graphic panel to depict the key parts of the process and a sequence timer with which the whole start-up routine could be performed automatically. It may be interesting to note that the graphic panel was eventually considered of doubtful value to the operators while some machinemen preferred not to use the automatic start-up. However, the benefit in having the switches in sequence on a single panel was thought to be definitely worth the capital expense involved and the additional cost on top of that for making a graphic panel and incorporating the automatic sequence timer was marginal.

1C.4 3 Shut-down

For an ordinary scheduled shut-down the machine chest will usually be run down as low as possible before stopping the chest pump. The substance of the sheet will immediately begin to drop as the head in the stuff box falls and at some point shortly after this the sheet is broken down at the couch. The wire is slowed, stuff valve closed, mixing pump stopped, and sprays switched over to fresh water. If fibre is retained the hog-pit and main pit may be washed out through the save-all, but normally they will be washed to drain through the dump valve and pits. The wire is finally stopped, the sprays turned off, and other parts of the wet-end, the screens, perforated rolls, etc., closed down.

Cleaning of the wet-end is usually accomplished with a high-pressure water jet to which special nozzles may be attached for various jobs. All inspection plates and drains should be opened and pipework and breast box parts thoroughly cleaned in this way, the more so when slime collects on the machine. If the wire has been cut off a more complete wash-up may be undertaken by pumping a caustic solution, possibly with a little insecticide added, right through the main flow system, a procedure adopted more commonly on faster machines with a great deal of enclosed boxes and pipework. The solution is placed in the backwater pit, heated if

necessary, and pumped round through cleaners, screens, breast box and slice; periodically the machine chest may also be filled and the chest pump and stuff box cleaned in the same way, as may the broke system, whitewater system, particularly sprays, and the preparation plant when necessary. In every case when the cleaning is finished the caustic solution must be drained out and sufficient fresh water should be circulated to flush the system clear.

For an emergency shut when the wire has to be stopped immediately, the stuff valve must be closed as quickly as possible and the sprays turned to fresh water to avoid marking the wire with whitewater jets. On machines with a dump valve to the main pit this can be opened; alternatively the mixing pump is stopped. When these steps have been taken to make the wire safe and prevent excessive accumulation of stock or water in the system which would make starting-up difficult, attention can be given to the other normal details of shutting and to the trouble in hand. It is at such times as this that a central control panel is invaluable, and use of pneumatically operated valves enables the process of stopping the wire to be accomplished rapidly by pressing a single button (see 1B.5 2).

1C.4 4 Changing quality and substance

More than with any other part of the paper machine, a change in quality affects the running of the wet-end and is dependent on the design of the system. On slower machines a colour change will rarely necessitate a complete shut-down and clean out; such machines are designed to facilitate changing and customarily have two machine chests so that one may be cleaned out and filled with the new furnish while the other is run down and cleaned out afterwards when the machine is under way again. In some cases it may be quite possible and economical to run through from one colour to another, tearing up paper made in the transitional stage; but often the whitewater system will only be rudimentary, with none leaving the machine house for dilution purposes earlier in stock preparation plants and in this case for a difficult colour change it is only necessary to empty the wire pit and save-all and fill up with fresh water. Rapid colour changes are facilitated by adding dyes and broke recovered from a save-all as late in the system as possible consistent with thorough mixing, an adequate residence time, and compatibility with alum addition; when this can be arranged after the machine chest, i.e. all fresh stuff from the preparation plant is uncoloured, then whether it is necessary to wash out the wet-end or simply run through, the time for changing is low, matching is rapid, and the risk of loss due to overcolouring in preparation is avoided.

But on faster machines with an elaborate whitewater system a colour change may necessitate draining out the whole system, whitewater, broke and all, exactly as for a week-end shut. Not until the system has been thoroughly cleaned out can the new colour be run. Normally, of course, this is obviously uneconomical and on such machines changes in furnish are confined to differing proportions of pulps and varying degrees of refining. In this case the machine chest can be run down as far as possible before changing the furnish but the machine is never stopped and the

paper made during the transition period is torn up. The economics of these different types of change depend primarily on the time involved and the characteristics of the machine; what may be satisfactory to suit a rare contingency in the order book would often be most unprofitable as a regular routine. Certainly any regular change-over warrants careful planning.

For a straightforward change in substance the situation is much easier. On slow machines with variable deckle the machineman will determine the alteration to speed necessary to take care of the change in substance, and at the same time an alteration in stuff valve or gate position may be necessary to accommodate the change in deckle. The machine speed may be fixed so that the production per foot width will be about the same while the stuff valve is altered pro rata with the deckle. Precisely the same applies to faster machines with no deckle change but in this case the stuff valve will probably not be touched.

The general validity of these remarks depends essentially on the degree of substance change required. On fine machines the substance may be increased fourfold and this obviously requires other considerations to be taken into account when compared to a change of a few g.s.m. on a fast news machine. To take the latter case first, no change in treatment of the furnish should be necessary and if drainage or drying capacity is assumed to be the limiting factor then production is kept about the same and the only alterations required to obtain the new substance are appropriate adjustment of the machine speed and head at the slice. With the stuff valve unaltered in position the drainage and drying demand is effectively unaltered and, as examined in the theoretical section, the consistencies at the wet-end are also unaltered if the change in head is effected by opening up the slice gap. In practice the head will probably be altered by changing the backwater circulation and for a small substance change this is perfectly satisfactory. Effecting such a change is a straightforward procedure involving (for a substance increase) lowering of the head, which will bring back the dry-line, followed by a drop in the machine speed, the same steps repeated as often as necessary to avoid upsetting the machine. For a substance decrease the reverse procedure is used.

If, on the other hand, machine speed is limited and for a decrease in substance production must be reduced, then a proportional change to the stuff valve would be necessary. In these circumstances this is probably the only alteration that would be made until the new position of the dry-line and vacuum in the suction boxes indicated the desirability of altering the backwater circulation.

For a more considerable change in substance the wetness of the furnish will be altered and then the changes on the machine must be more dependent on gradual alteration of conditions to keep the dry-line and suction box vacuum steady. The slice gap will invariably need alteration in addition to the other changes detailed above and its final position will depend more than anything else on the relative difference in drainage on the wire due to the alteration in substance and beating. Especially on machines making such large changes in substance an appreciable saving is possible with the aid of a beta-ray gauge at the dry-end to monitor the effect of the various

adjustments made during the change-over. Also, as at a start-up, the normal positions of the valves, slice, gauges, etc. for the new substance should be known from past running and this will help the machineman to achieve the desired conditions quickly. It is in this sphere especially that on-line computers which can carry out a grade-change automatically and in a minimum time are presenting a high rate of economic return.

1C.4 5 Checking the wet-end flow system during running

The importance of the various gauges and recorders which can be found through the wet-end flow system has been dealt with in detail in 1C.1 and their use to the machineman in keeping a check on general running conditions requires no further elaboration. The majority of these measurements serve either to show whether running conditions differ from normal or to allow more accurate setting of the conditions than would otherwise be the case. The flow of stock to the breast box, or in a rougher but more common way, the gap between the slice lips are particularly important when used in association with the position of the dry-line since they give the machineman a systematic indication of whether drainage is satisfactory or whether the stock is working wetter or freer on the wire. Similarly a slice head measurement compared to wire speed, by assisting in setting the relative speeds of jet and wire, draws attention to a highly important aspect of formation which it is difficult to judge by eye except on slow machines.

These features apart, inspection at the wet-end so far as the flow system is concerned largely comes down to such matters as checking that the sprays are functioning adequately, that pressures in the pipe system are satisfactory, chemical, loading, and dye addition is steady, perforated roll drive is running, and the whitewater system and save-all are in order. The presence of slime, pitch, foam, and fibre clumps in the whole flow system will obviously be noted and steps taken to eradicate the trouble by, if necessary, shutting the machine for a wash-up; prevention of these nuisances has been considered in 1C.2, and removal of slime and pitch from the wire part where they are most troublesome will be dealt with in Part 3. Levels in pits, tanks, stuff box, and breast box require checking, whether they are controlled or not; the liquid surface and walls of the breast box, when observable (which should always be the case), whould be examined to ensure the sprays are keeping down froth and scum, also that no violent disturbance is present on the surface which could affect the evenness of slice discharge. The slice itself should always be scrupulously clean and the effect of dirt and fibre clumps lodged under the lips is readily detected in the flow on the wire; the edges of the slice can also be affected by a build-up of lumps of fibre and require careful inspection. Keeping the substance both across and along the web steady usually occupies a fair proportion of the machineman's time, especially on a machine which is poorly controlled and relatively unstable, and this topic has already been discussed in detail. Otherwise the attention of the machineman is directed mainly to the wire part and, though in practice the flow system and the wire part are inspected together, further details of the latter will be deferred till Part 3.

REFERENCES

(1) Hansen, E.: 'The Distribution of Filler in Paper.' TAPPI 34, 4, 180. April, 1951.
(2) Bienkiewicz, B., Mardon, J., and Robinson, W. F. E.: 'Studies in Backwater Systems.' Part I—'Theoretical Principles of Backwater Systems, Operation and Methods for Material Balance Construction.' Proc. Tech. Sec. 33, 2, 383. May, 1952.
(3) Bienkiewicz, B., Mardon, J., Robinson, W. F. E., and Scruton, H.: 'Studies in Backwater Systems.' Part II—'Examples of Closed Systems in Operation.' Proc. Tech. Sec. 33, 2, 395. May, 1952.
(4) Hendry, I. F., Mardon, J., Scruton, H., and Wilkinson, D. M.: 'Drainage on a Tissue Machine Wire Table.' Proc. Tech. Sec. 33, 3, 603. December, 1952.
(5) Mardon, J., Robinson, W. F. E., and Wilkinson, D. M.: 'Studies in Backwater Systems.' Part III—'Operation of Closed System: Papermaking Considerations.' Proc. Tech. Sec. 33, 2, 408. May, 1952.
(6) Sergeant, S. V.: 'Some Flow Box Investigations.' Proc. Tech. Sec. 33, 1, 49. February, 1952.
(7) Chartrand, J. Y.: 'Automatic Control with the Betameter.' P. and P. Mag. Can. 54, 5, 109. April, 1953.
(8) Duskin, A. W. and Jenkins, W. B.: 'The Deculator on a Kraft Paper Machine.' TAPPI 36, 11, 490. November, 1953.
(9) Wilson, G. E.: 'The Betameter in a Basis-Weight Control Application.' P. and P. Mag. Can. 54, 3, 224. Convention Issue, 1953.
(10) Bennett, W. E.: 'Quantitative Studies of Water Removal by Table Rolls.' TAPPI 37, 11, 534, November, 1954.
(11) Gavelin, G.: 'Some Effects of Gases on Properties of Fibre Suspensions.' P. and P. Mag. Can. 55, 3, 191. Convention Issue, 1954.
(12) Mardon, J. and Van Der Meer, W.: 'Flocculation, Formation and Headbox Design from the Aspect of Turbulent Motion.' P. and P. Mag. Can. 55, 9, 107. October, 1954.
(13) Mason, S. G.: 'Fibre Motions and Flocculation.' TAPPI 37, 11, 494. November, 1954.
(14) Mason, S. G., Robertson, A. A., and Allen, G. A.: 'Turbulent Diffusion in Fourdrinier Machines.' P. and P. Mag. Can. 55, 8, 97. August, 1954.
(15) Robertson, A. A. and Mason, S. G.: 'Flocculation in Flowing Pulp Suspensions.' P. and P. Mag. Can. 55, 3, 263, Convention Issue. 1954.
(16) Van Den Akker: 'Flow in Fibre Suspensions and the Effects of Turbulence.' TAPPI 37, 11, 489. November, 1954.
(17) Van Der Meer, W.: 'Hydraulics of Flowbox and Slice.' TAPPI 37, 11, 502. November, 1954.
(18) Bearer, G. F.: 'Automatic Control of Basis Weight Using Radioisotopes.' TAPPI 38, 1, 139A. January, 1955.
(19) Jacobsson, J. J.: 'De-aerating of Paper Stock for the Paper Machine.' Proc. Tech. Sec. 36, 2, 387. May, 1955.
(20) Landesman, A. L.: 'The Role of Flow Control in Basis Weight and Caliper Control.' TAPPI 38, 5, 148A. May, 1955.
(21) Mardon, J., Gavelin, G., and Logan, K. C.: 'The Effect of Some Machine Characteristics on Paper Uniformity.' P. and P. Mag. Can. 56, 3, 275. Convention Issue, 1955.
(22) Baines, W. D. and Nicholl, C. I. H.: 'Hydrodynamics of the Fourdrinier Wet-End. I. Fibre Orientation in Pipe Flow.' P. and P. Mag. Can. 57, 6, 119. May, 1956.
(23) Boadway, J. D.: 'Gas in Papermaking Stock.' P. and P. Mag. Can. 57, 3, 185. Convention Issue, 1956.
(24) Mardon, J., O'Blenes, G. and Ryan, J. A.: 'Hydraulic Measurements in Paper Machine Headbox Design and Operation.' Svensk Pap. 59, 12, 429. June, 1956.

95

(25) Mardon, J. and Shoumatoff, N.: 'Flocculation, Formation and Headbox Design. Part IV.' P. and P. Mag. **57**, 3, 305. Convention Issue, 1956.

(26) Robertson, A. A. and Mason, S. G.: 'Hydrodynamics of the Fourdrinier Wet-End. II Pipe Flow and Fibre Flocculation.' P. and P. Mag. Can. **57**, 6, 121. May, 1956.

(27) Underwood, N. C. and Shipstone, B. A.: 'Reduction of Basis Weight Variation on a Newsprint Machine.' Canadian Tech. Sec. Proc. p. 510, 1956.

(28) Van Horne: 'Evaluation of Beta Gauge Control System.' TAPPI **39**, 12, 193A. December, 1956.

(29) Bennett, H. W.: 'The Flow Characteristics of Distributor Rolls and Perforated Plates.' TAPPI **40**, 12, 978. December, 1957.

(30) Cuffey, W. H.: 'Some Factors Involved in Basis Weight Uniformity.' TAPPI **40**, 6, 190A. June, 1957.

(31) Eastwood, G. G. M. and Gade, M. F.: 'Instrumentation for the Automatic Start-Up of the Wet End of a Paper Machine.' TAPPI **40**, 6, 403. June, 1957.

(32) Robertson, A. A. and Mason, S. G.: 'The Flow Characteristics of Dilute Fibre Suspensions. TAPPI **40**, 5, 326. May, 1957.

(33) Anon: 'Instrumentation and Automatic Control at Aylesford.' Paper Maker **86**, 5, 50. November, 1958.

(34) Baines, W. D.: 'The Influence of a Simple Surge Tank on Pressure Oscillations in a Piping System.' P. and P. Mag. Can. **59**, 3, 177. Convention Issue, 1958.

(35) Bonnington, S. T.: 'The Frictional Losses of Paper Stock in Pipes.' Proc. Tech. Sec. **39**, 2, 257. June, 1958.

(36) Evans, J. C. W.: 'Hamilton Completes Major Expansion with many Interesting Features.' Paper Trade Journal **142**, 41, 38. December 22, 1958.

(37) Forgacs, O. L., Robertson, A. A., and Mason, S. G.: 'The Hydrodynamical Behaviour of Papermaking Fibres.' P. and P. Mag. Can. **59**, 5, 117. May, 1958.

(39) Mc.Nown, J. S. and Spengos, A. C.: 'A Preliminary Study of the Instability of the Stock on the Wire of a Fourdrinier Paper Machine.' TAPPI **41**, 1, 9. January, 1958.

(40) Mardon, J., O'Blenes, G., and Wahlström, P. B.: 'The Hydrodynamics of Paper Machine Headbox Approach Piping.' P. and P. Mag. Can. **59**, 4, 139. April, 1958.

(41) Paterson, H. A. and Hazeldine, E.: 'Mixed Stock Control System at Mersey Paper Co. Ltd.' P. and P. Mag. Can., **59**, 3, 279. Convention Issue, 1958.

(42) Reitzel, N. M.: 'An Investigation of Hydraulic Pressure Pulsations in Wet-End Piping of a Paper Machine.' P. and P. Mag. Can. **59**, 3, 184. Convention Issue, 1958.

(43) Anon: 'The Egger Diaphragm Regulating Valve.' Das Papier **13**, 11/12, 268. June, 1959. (In German).

(44) Brecht, W., and Kirchner, U.: 'The Air Content of Paper Stock.' Woch. fur Pap. **87**, 8, 295. April, 1959. (In German). Summary in Paper Maker **138**, 2, 60. August, 1959.

(45) Müller-Rid, W. and Pausch, G.: 'Studies on the Slice of a Newsprint Machine.' Woch. fur Pap. **87**, 11/12, 478. 1959 (In German). Summary in Paper Technology **1**, 1, 11 February, 1960.

(46) Reitzel, N. M.: 'A Wide Range Pressure Inlet: Design and Operation.' TAPPI **42**, 2, 137. February, 1959.

(47) Ure, R. A., Nuttall, G. H., and 'Lay Boy.': Keeping Down Froth on a Paper Machine.' Paper Maker **138**, 1, 36. July, 1959.

(48) Anon: 'British Made Machine Installed in German Mill.' Paper Trade Review **153**, 21, 1899. May 26, 1960.

(49) Attwood, D. and Alderson, J. P.: 'The Use of a Large Model to Study the Flow Pattern of an Open Flow Box.' Paper Technology **1**, 6, 653. December, 1960.

(50) Brewden, H. A., and Locking, B.: 'New Developments in Paper Machine Headbox Design and Equipment.' Paper Trade Journal **144**, 31, 36; 32, 24; 33, 38. August 1, 8 and 15, 1960.

(51) Gardner, R. C., and LeBreton, L.: 'Instrumentation of a Paper Machine.' Paper Technology **1**, 3, T82. June, 1960.

(52) Howarth, J. and Banks, W. A.: 'Machinery for Automation.' Paper Technology **1**, 3, T112. June, 1960.
(53) Mardon, J., and Wahlström, B.: 'The Characterisation of some Modern Head-boxes by the use of Hydraulic Measurements.' Svensk Pap. **63**, 20, 716. October 31, 1960.
(54) Müller-Rid, W. and Pausch, G.: 'The Effect of Operating Conditions on Sheet Formation.' Das Papier **14**, 12, 647. 1960. (In German). Summary in Paper Technology **2**, 2, 186. April, 1961.
(55) Nelson, H. C.: 'Paper Machine Inlet Performance in Relation to the Fourdrinier Wire.' TAPPI **43**, 4, 330. April, 1960.
(56) Smith, B. W.: 'Scanning Basis Weight and Moisture Gauges Systems on Paper Machines.' TAPPI **43**, 3, 226. March, 1960.
(57) William, D. J.: 'A Continuous Freeness Recorder for Pulp Suspensions.' TAPPI **43**, 7, 613. July, 1960.
(58) Anon: 'New Machine boosts Fine Paper output in latest Wassau Expansion.' Paper Trade Journal **145**, 40, 20. October 2, 1961.
(59) Anon: 'How much do you know about Knife Slices?' Paper Trade Journal **145**, 51, 39. December 18, 1961.
(60) Attwood, D.: 'The use of a Beta-Gauge for Automatic Basis Weight Control.' Paper Technology **2**, 1. T19. February, 1961.
(61) Barker, E. F.: 'Unique Bruderhaus Organisation Installs New Paper Machine in Own Mill.' Paper Trade Journal **145**, 1, 20. January 2, 1961.
(62) Brecht, W. and Kirchner, U.: 'The Air Content of Pulp Suspension.' Das Papier **15**, 10a, 625. 1961. (In German.)
(63) Chedomir, G. A.: 'Continuous Freeness Recording Controller.' TAPPI **44**, 6, 220A. June, 1961.
(64) Harman, G. L.: 'Continuous Freeness Measurement and Control.' Paper Trade Journal **145**, 34, 54. August 21, 1961.
(65) MacLaurin, M. I.: 'Instrumentation—its Success and Delusions.' Svensk Pap. **64**, 10, 394. May 31, 1961.
(66) Moore, M., and Walsh, E. P.: 'Discussion of some News Machine Wet-End Operating Variables.' P. and P. Mag. Can. **62**, 5, T-293. May, 1961.
(67) Parker, J. D.: 'Recent Theoretical Work in the Area of Sheet Formation.' TAPPI **44**, 4, 162A. April, 1961.
(68) Van Derveer, P. D.: 'New Machine Boosts Nekoosa-Edward's Fine Paper Production.' Paper Trade Journal **145**, 9, 1-8. February 27, 1961.
(69) Vercoe, J. E.: 'Fourdrinier Maintenance—Key to Machine Efficiency and Wire Life.' Paper Trade Journal **145**, 14, 36. April 3, 1961.
(70) Cuffey, W. H., and Ingram, G.: 'Cyclic Machine Direction Basis Weight Variation.' P. and P. Mag. Can. **63**, 4, T-203. April, 1962.
(71) Mac Gugan, I. C.: 'Calcium Chloride—An Effective Stock Drainage Aid.' Paper Trade Journal **146**, 2, 22. January 8, 1962.
(72) Müller-Rid, W., Stark, A., and Pausch, G.: 'European Thoughts on Paper Machine Stock Distributors and Stock Inlets.' Paper Trade Journal **146**, 1, 26. January 1, 1962.
(73) Rathman, H.: 'Slime Formation and Slime Control in Paper Mills.' Book Review by Russell, P. in Paper Technology **3**, 3, 252. June, 1962.
(74) Wrist, P. E.: 'Dynamics of Sheet Formation on the Fourdrinier Machine.' Formation and Structure of Paper. Transactions of the September 1961 Oxford Symposium, p. 839. B.P. & B.M.A. Tech. Sec. publication, 1962.
(75) Anon: 'Round-up Report on Three Continuous Freeness Testers.' Paper Trade Journal **147**, 10, 38. March 11, 1963.
(76) Beecher, A. E.: 'Dynamic Modelling Techniques in the Paper Industry.' TAPPI **46**, 2, 117. February, 1963.
(77) Mardon, J., Manson, D. W., Wilder, J. E., et al.: 'The Design of Manifold Systems for Paper Machine Headboxes.' Part I 'Branching Pipe Manifolds.' P. and P. Mag. Can. **64**, 2, T-35. February, 1963. Part II 'Taper Flow Manifolds.' TAPPI **46**, 3, 172 March, 1963.
(78) Robinson, D. E.: 'The Detection of Pulsation and Consistency Variation in Jet Inlet Flow.' P. and P. Mag. Can. **64**, 3, T-169. March, 1963.

SCREENS AND CLEANERS

INTRODUCTION

21 An essential part of the operation of making paper on the Fourdrinier is removal from the stock of impurities and tangled mats of fibre which spoil the appearance of the sheet, are a source of breaks, and in some cases increase wear of the wire and calender rolls. The growing standards of converters and greater speeds of converting and printing machinery ensure that this function is continually increasing in importance, even though pulp itself, whether imported or prepared at the mill, has been improved appreciably in cleanliness to meet the needs of the papermaker. A measure of the value now attached to efficient purification of stock is that even newsprint machines are being equipped more and more with both screens and cleaners, despite the heavy increase in capital and running costs.

This part of the book is concerned with the design and operation of equipment used at the wet end of a paper machine for the removal of unwanted material in the stock. Equipment for the same purpose is, of course, used in pulp mills where it is generally similar in design and in most cases can be readily interchanged with units in the paper mill. However, certain models are normally found only in pulp mills, particularly those concerned with the coarse screening and cleaning of pulp or having some specialized function such as the magnetic separation of ferrous particles. Also some models are designed primarily for use on particular types of pulp, esparto, rag, wood, etc., and some are intended for use at relatively high consistencies more usual in the pulp making process. Attention is confined here solely to equipment commonly in use on the paper machine, which implies that it is used on diluted stock between the mixing pump or box and the breast box at a consistency normally under 1 per cent.

The operation of a piece of screening or cleaning equipment is closely related to the actual design. Though two models may have precisely the same function and have been designed with removal of the same kinds of impurity in mind, their actual construction, performance, and running can be totally different. For this reason in what follows it has been found convenient to divide the chapter which deals with operating factors affecting screens and cleaners according to the various main categories of equipment available. The chapter on theory is divided in a straightforward manner between screening and cleaning as a whole, with an additional piece on methods of assessing the efficiency of removal of impurities. The final chapter on the running of screens and cleaners follows the pattern adopted throughout the book for each section of the Fourdrinier.

21.1 Different types of equipment

It will be as well, at the outset, to be clear on what is meant by 'screens' and 'cleaners'. The two terms are often used loosely, particularly in the

101

expression 'screening equipment' which is frequently meant to cover both types. Confusion arises too because a screen can be said to clean stock in the sense that it removes certain types of impurity, while a cleaner also acts to some extent as a screen.

The distinction becomes reasonably clear if a screen is thought of as a piece of equipment which separates essentially by size, while a cleaner separates by density. On this basis to 'screen' means to direct the paper stock through small holes or slots and thereby keep back anything that is not small enough to pass through. To 'clean' means in practice to subject the stock to forces, usually centrifugal, which cause particles of different density to go in different directions so that a separation can be effected. Most screens and cleaners also tend to break down or deflocculate tangled clumps of fibres: screens by the action of a vibrating or pulsating mechanism, cleaners because of the heavy shear forces that occur in the flow.

Screens come in a variety of types which for convenience can be divided as follows (the more common makes are given in parentheses):

> flat diaphragm (Watford, Jonsson, Sherbrooke, Parker)
> rotary outward flow (Wandel, Walpole)
> rotary inward flow (Bird, Voith, Leith-Walk, Watford)
> enclosed pressure (Selectifier, Centriscreen, Finckh, Lamort, Durafiner)

Cleaners can be divided into:
> sand traps or rifflers
> rotating basket (Erkensator, Purifuge, Centrifiner)
> cylindrical (Dirtec, Vortrap, Vorject, Voith Tube Separator, Hydraclone)
> cyclone (Centricleaner, Berg, Radiclone, Hy-Cleaner)

A great number of these models are now obsolete, though many are still in use so brief comment on them will be made in the appropriate place.

There are in addition to those listed above several rather specialized designs, for example high-frequency rotating screens (e.g. Vibrotor) used before dilution with backwater (but nevertheless at a consistency as low as 1 per cent.) on kraft machines where cleanliness is of relatively little importance; such models will be mentioned only insofar as details of their operation have some bearing on the more general types employed on paper machines.

Other types of equipment find their way into paper mills but are, strictly speaking, designed specifically for use on pulp and are not incorporated as part of the paper machine system itself. This applies to models such as the Centriffler, a bulk trash remover commonly used in waste paper stock preparation. This type also is not dealt with in what follows.

Finally, it is as well to clarify terminology. In this work the flow to any screen or cleaner will be referred to as the 'inlet flow'. At the screen or cleaner this divides into an 'accept flow' containing (it is hoped) fewer impurities in relation to fibre, and a 'reject flow' containing a greater proportion of impurities. The reject flow is normally either re-treated in further screening or cleaning equipment or led to drain. Inlet, accept and

reject flow refers to the whole flow; occasionally it will be necessary to refer to the individual constituents and then the terms 'fluid', 'fibre' or 'dirt' flow will be used. 'Efficiency' used in a general sense means simply the ability of a screen or cleaner to separate impurities from fibre. It will be necessary later to define particular aspects of this more carefully.

2I.2 Choice of equipment

The wide range of screening and cleaning equipment, and the variety of quite different principles of operation, makes it extremely difficult to select the most appropriate for any particular situation. Because of the problems involved in assessing the efficiency of screens and cleaners when they are actually in operation, there is little to guide the papermaker to a sound decision and as often as not a selection is made on the basis of capital required, running costs, and reports of easy operation and maintenance. Such information as is available on the comparative performance of the various models, and what applications they appear best suited for, is presented below in an attempt to clarify the position in this respect.

No installation or alteration of cleaning and screening equipment should ever be undertaken without having a clear idea of what impurities (using the term in a general sense) are present in the stock, and what standard of cleanliness is being aimed at. Impurities can take a multitude of forms:

- (a) pure contaminants within the pulp (shives, esparto roots and dust, undisintegrated bark, pitch, unbleached clumps of fibre, undissolved lumps, etc.)
- (b) other contamination of the pulp (grinder grit, boiler scale, sawdust, rust particles, etc.)
- (c) external contamination in the paper mill (dirt off bales, especially grit and coal, bale wire, sand, sisal hairs, fresh water impurities, loading impurities, rubber and plastic pieces, bitumen, airborne dirt particularly boiler fly ash, etc.)
- (d) internal contamination (pipe scale, rust particles, wood chips, lumps of cement, beater and refiner metal, slime, oil, spanners, etc.)
- (e) stock contamination (uncleaned pieces of broke, tangles and strings of fibre, poorly dyed clumps, unrefined lumps, etc.).

No single cleaner or screen can be expected to remove all of these; in any case certain types of contaminant are always more serious on a particular machine than others. Then again, the motive in wanting certain impurities removed can vary: on one machine it may be purely a question of obtaining as clean a sheet as possible, on another of reducing breaks on the paper machine itself or afterwards during converting, and on yet another of promoting wire and calender roll life by getting rid of abrasive materials in the stock. In other cases it may be a matter mainly of overcoming persistent blotches in the sheet which are caused by poor drying round large particles; in bad circumstances such damp patches are dis-

torted in the calenders by a miniature crêping effect or can be stamped out completely to leave a hole.

The task required of a cleaner or screen on any particular machine will frequently alter appreciably according to the furnish and grade being run. Also the standard of cleanliness demanded varies enormously from minimal on a grade such as kraft wrapper, important on newsprint and printing papers, high on bleached papers, up to crucial on specialized grades such as photographic base. It is thus unfair to expect any new piece of equipment to solve all difficulties arising from impurities, particularly if these have not been carefully enumerated beforehand and some idea obtained of just what has to be removed from the stock. Recognition of the enemy by analysis of impurities found in the paper and in the stock should always be the first step, if only because in many cases such impurities are produced in the mill and it can be far cheaper and more practicable to prevent them entering the system in the first place.

CHAPTER 2A

THEORETICAL CONSIDERATIONS

2A.1 THEORY OF SCREENING

No detailed theory of screening paper stock has yet been formulated, nor has any investigation been reported which gives fundamental data that could form a basis for a theory of screening. Details of the performance of one or two models of screen with respect to particular types of contaminant have appeared from time to time, but to the author's knowledge there has been no attempt under controlled conditions to discover the effect of the various variables involved in the screening action. These include such factors as throughput, rejection rate, hole variables (size, shape, thickness), and oscillation characteristics, and their effect on different types of contaminant under different stock conditions of fibre, consistency, wetness, and so forth. Nevertheless, certain general information on the screening action is known and this is presented below.

2A.1 1 The screening action; basic ideas

The action of screening is essentially one of size discrimination, but the extent of this discrimination when applied to paper stock is by no means easy to predict. Some understanding of what is involved can however be built up from certain elementary considerations.

The simplest example of this form of separation is the passage of dry, solid spherical particles falling under gravity through a sieve. Ideally each particle of a diameter smaller than the diameter of the sieve hole (or the side of the square formed in a mesh) should pass through and the remainder be rejected. But in practice this is modified by the manner in which the sieving takes place and it is instructive to consider one or two aspects of this.

In the first place, a particle of small diameter falling onto the sieve will be unlikely to pass straight through. If it were extremely small, the chance of immediate passage will be equivalent to the open area of the screen, i.e. if this is 75 per cent. then the particle will have a 75 per cent. chance of passing straight through. Larger particles will have less chance than this of being accepted because the greater contact area they present must, to permit direct passage through, correspond with a free space in the sieve; it is evident that this only occurs when the centre of the particle meets the sieve in such a way that it is over a free space and at the same time more than a radius length from the edge of the space. For example, if the sieve contains circular holes it is easy to show that the probability of acceptance of a spherical particle at a first pass can be expressed as

$$p = \frac{h\,(r_s - r_p)^2}{r_s^2},$$

where r_p is the radius of the particle, r_s the radius of holes in the sieve, and h the proportion of open area. Under these conditions, for a sieve with 75 per cent. open area the relationship between probability of first passage and radius of the particle is illustrated in Fig. 2.1.

In practice this probability would be slightly greater due to the possibility of a particle glancing the edge of a hole but nevertheless passing through. More important though is the effect on this probability of further attempts (after bouncing) to pass through the sieve. An example of this
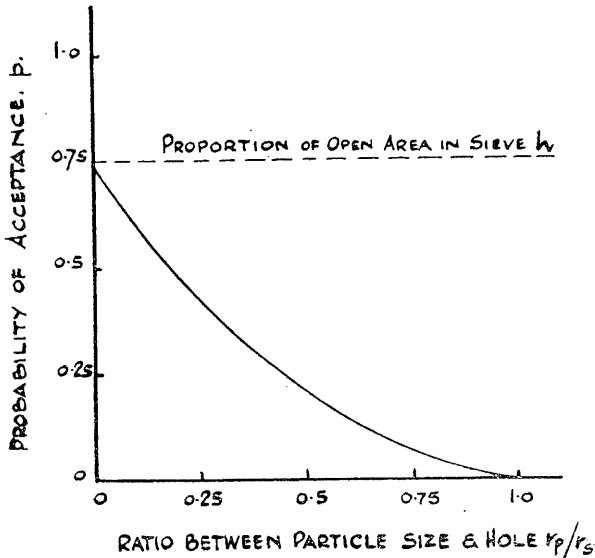
Fig. 2.1. Relationship in an ideal situation between spherical particle size and probability of acceptance through a 75 per cent. open sieve with circular holes

for particles one quarter and one half the size of holes in the same sieve is shown in Fig. 2.2. This illustrates the growth of probability of acceptance with repeated attempts to pass the sieve.

Two points of importance emerge from these simple examples. Firstly, in an ideal screening operation the chance of a spherical particle being accepted increases appreciably as its size decreases below the size of the hole in the sieve. Secondly, this probability increases also with the number of passes of the sieve attempted by the particle, or put another way with the average residence time of the particle on the sieve. Given sufficient time, the probability of any particle less than the hole size being accepted becomes a near certainty.

2A.12 The screening action; particle interaction

So far attention has been confined to the screening action on a single particle. To take this a stage further it is necessary to consider the situation

106

when there is a flow of various sizes of particles being screened as a continuous process. What effect is particle interaction likely to have on screening efficiency?

It is evident for a start that the density of particles falling on the sieve will affect the performance. The less the average space between particles, the more likely their path is to be interrupted. However, this in itself should not significantly alter the probability of an individual particle passing through at any time because interaction between particles can be presumed random. Density will affect the performance more directly insofar as particles larger than the hole size tend to cover or lodge in the
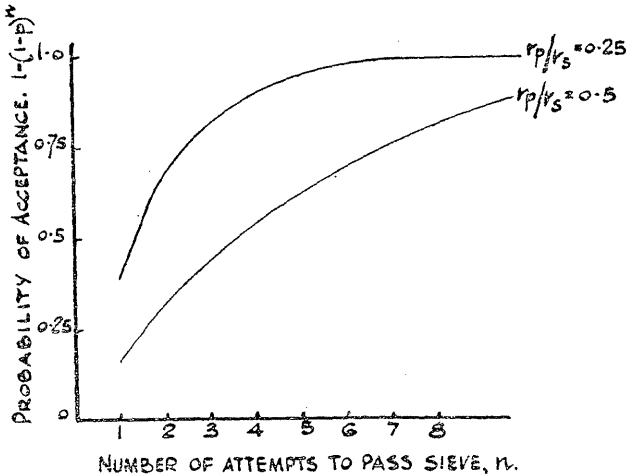
Fig. 2.2. Relationship in an ideal situation between probability of acceptance of spherical particles one quarter and one half the size of holes in a 75 per cent. open sieve with the number of attempts to pass the sieve

holes and block them, thus reducing the area available for free passage; the greater the density of a given flow, the more will larger particles gather in the region of the sieve to restrict passage of smaller particles. The extent of this interference will evidently depend on the proportion of large particles in the flow, in other words on the size distribution, and on the average length of time the particles are allowed to remain in the vicinity of the sieve plate before passing out as reject.

Taken together, these points illustrate several fundamental considerations in screening. Firstly, it is obviously necessary to agitate the flow of particles either by vibration of the screen itself or, alternatively, of the medium carrying the particles. Without some form of agitation the holes of the screen will rapidly clog up. Secondly, the density and size distribution of particles will affect the time that can be allowed for screening: if this is too long the region next to the screen will pack down with larger particles and gradually inhibit flow altogether, even with reasonable

107

agitation. As residence time on the screen determines the average number of passes a particle can attempt and hence the probability of it getting through, it is evident that the greater the density and the higher the proportion of larger particles, the lower the average probability of acceptance becomes due to the necessity of reducing residence time to a level where the screen continues to work.

It is at this point that recourse to experiment becomes necessary. In any practical case, to find the best working conditions it would be necessary to investigate the effect on the performance of varying residence time and different forms of vibration. As residence time is increased it can be expected that performance will at first increase but then, as the point of clogging is approached, begin to decrease. This latter point would define the maximum flow of particles the screen could cope with in the conditions pertaining.

Further considerations inevitably arise when the carrying medium itself has a density comparable to the particles, i.e. in practical terms when it is water rather than air. This introduces hydrodynamic complications because the flow of water will channel through the holes of the screen, tending to carry with it the smaller particles. This of course should be advantageous. Also the transmission to the particles of vibrations applied to the screen will be more effective in a denser medium.

2A.1 3 Screening action on paper stock

The screening action considered so far has one important feature; although there is always a certain probability of particles smaller than the holes passing through, it is physically impossible for any larger particles to pass. In screening terms this means that the cut-off is very sharp and exclusion of all particles above a certain size (that of the holes) is a certainty. This will always apply to rigid particles in any screen, but immediately it becomes possible for the shape of the particle to distort or flex, the whole character of screening changes.

Exclusion of large particles generally has far more importance in any screening operation and if the cut-off is not sharp it is of special interest to know the size at which the probability of larger particles passing becomes negligible. This is a feature of any screening operation of flexible particles that can only be determined experimentally because of the numerous factors that come into play: the degree of flexibility of the particles, the head above the screen (which affects the pressure producing distortion of shape), the elasticity of the particles, and so on.

With fibres and shives in paper stock, the element of flexibility overrides most others. The shape of a fibre can alter at will, especially when beating has imparted a greater flexibility, and it is also known that fibres are compressible in their cross-section. In theory it should be possible for any fibre to pass through a hole of a diameter comparable to its cross-sectional area, which in practical terms implies that all fibres would pass through the holes used in commercial screens.

The reasons this does not occur are basically twofold: the element of

probability introduced by the fact that only a proportion of fibres will approach a hole endways on, and the interaction of fibres caused by their tendency to entangle mechanically. An analysis of the first point has been presented by Tirado (24) who calculated that the probability of a rigid fibre or shive of small cross-sectional area passing through a hole during screening is governed by its length in such a way that a minimum of one-third will be accepted whatever the length; when the length is less than the diameter of the holes this fraction increases. Interaction of fibres reduces the probability of acceptance when it results in their being entangled into a relatively large mass; the vibration of a screen plate should assist in practice to break down such clumps of fibres, but if this does not occur it is preferable anyway that they are not accepted. Interaction of fibres is also affected by consistency, being of course more likely when this is high, so fibres have a greater probability of acceptance at a lower consistency.

To summarize, screening efficiency on paper stock must by its nature represent an extremely imperfect operation. Ideally all individual fibres should be accepted and all impurities above a given size held back. But because of the limited capacity of a screen it is not possible to allow adequate residence time for each fibre to have sufficient opportunity to pass through a hole. So a proportion must be rejected, together with unbroken clumps of fibres which, though representing good fibre, it is necessary to remove anyway.

Likewise the probability of rejection of different impurities is governed by numerous factors, most important of which are the size, rigidity, and shape of the impurities, and the residence time on the screen plate; in most cases residence time is preferably kept short to reduce the chances an impurity has of getting through the holes. Solid particles larger in size than the diameter of holes in the screen are certain to be rejected; but other particles will always have some measure of probability of getting through with the accepted fibre.

A typical curve relating impurity size to probability of rejection is shown in Fig. 2.3. The minimum rejection for very small particles is seen to be effectively equal to the volume of flow in the reject as a proportion of the inlet flow (here about 5 per cent.), and as particle size increases complete probability of rejection is eventually approached. The slope of the upgoing part of the curve is a measure of the sharpness of cut-off: the steeper this is the better from a screening efficiency viewpoint. The 50 per cent. probability point (A) is often taken as a convenient measure of efficiency of rejection for comparative purposes.

A final element is the shape of hole: this is frequently in the form of a slot rather than a circular hole. It is evident that for the same open area this gives a smaller minimum cross-section, which implies that the cut-off point for rigid spherical particles will be lower. On the other hand rigid particles tending to be flat in shape will have some possibility of acceptance so long as their maximum cross-sectional diameter is less than the width of the slot, whereas with circular holes if the diameter of the hole is smaller than the maximum diameter of the particle passage is impossible. Using

109

slots instead of circular holes thus favours removal of spherical-shaped particles, but makes it more likely that flat shapes, especially in the form of shives, are accepted. This is of importance, as will be seen later, when considering the relative efficiencies of current types of enclosed screen, which generally have circular holes in the screen plates, compared to the older open rotary types which invariably have slots.

2A.1 4 Screening capacity

Whatever the conditions of screening, the most fundamental factor controlling performance is obviously the size of holes in the screen plate. The ideal situation is to choose a diameter of hole which will cut off
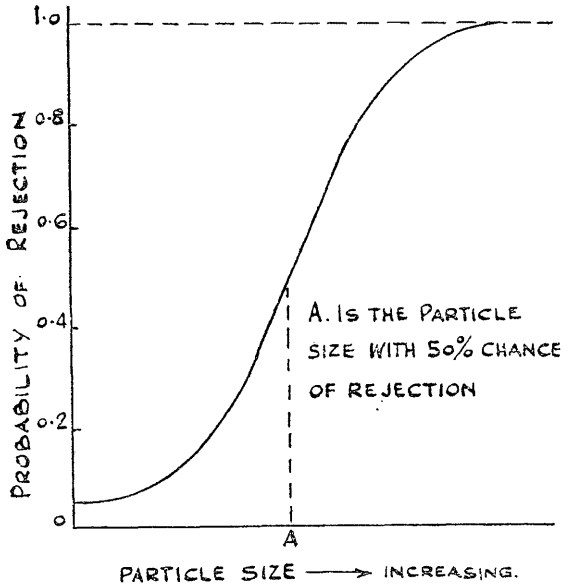
Fig. 2.3. Typical relationship between probability of rejection in a screen and size of impurity

impurities above a size which is well under that acceptable for the machine and paper. Unfortunately, this is rarely possible because of the effect of hole size on the capacity of a screen.

Even if the overall open area of a screen plate is kept constant, reduction in the diameter of holes brings about a rapid drop in the flow that any particular screen can cope with. This is primarily due to the greater tendency for holes to get clogged with impurities, coupled with a dewatering effect as fibres clump together at the entrance to holes. Vibration reduces this tendency, which is one reason why high-frequency vibrating screens have greater capacity, but there must always be some limitation

to flow dependent on the nature of the screen and composition of the stock it has to deal with.

Of particular importance in this respect is the manner in which impurities are removed from the screen plate in the reject flow. If this reject flow is effectively uncontrolled, as in most flat screens, reducing the hole size (other things being equal) has the effect of increasing the volume of reject. If the reject flow is controlled by some valve setting, reducing the hole size need only affect the volume insofar as pressure distribution in the screen may be altered; but the effect on the screen operation is to increase the power needed for the vibrating action and, in an enclosed system, the pressure loss across the screen plates. Eventually, if hole size is reduced sufficiently the screen either overflows if it is of the open type or seizes up if enclosed.

So inevitably some compromise is necessary in choosing hole size. The possibility of clogging or overflowing must be avoided, and where reject flow is effectively uncontrolled it is essential to be able to set the screen to keep this to a small amount. This is because once the point is reached where the screen can function satisfactorily no increase in efficiency occurs by having a large reject flow: the ability to remove impurities is virtually unchanged because conditions at the actual site of the holes are the same, and all that happens is that a greater quantity of good fibre is passed to the reject. When screening is to take place at a higher consistency, or with long fibres that are more likely to entangle and become stapled between holes, then obviously the compromise must err more to a larger size of hole.

This point is clearer when the case is considered where reject flow can be closely regulated. A certain minimum reject flow is of course essential to ensure that impurities are cleared from the screen plate and any tendency to clog or overflow is obviated. But it is a fallacy to believe that greater efficiency necessarily ensues from increasing this reject flow further. The basic operation desired of a screen is to separate out particles above a given size for a minimum loss of good fibre. In other words any alteration can only be deemed to lead to greater efficiency if it produces a lower proportion of impurities in the accept flow compared to fibre. It is rare that increasing reject flow has this effect: certainly a greater *number* of impurities may appear in the reject, but the proportional increase in relation to the fibre rejected is almost always lower so the cost of separation is proportionately higher and the efficiency consequently lower. Since increasing reject flow generally reduces efficiency in this way, it is only really permissible if the extra loss is worthwhile in order to reduce the overall number of impurities occurring at a particular time.

2A.1 5 The secondary screen

So far, attention has been confined to the action of a single screen. In practice this may of course comprise several identical units placed in parallel to give sufficient capacity to treat the required flow. Whether there are one or more individual units, when these treat the main stock flow line they are henceforth termed the primary screen.

The reject flow from the primary screen can comprise between about 2 per cent. and 10 per cent. by volume of the inlet flow. This contains too much good fibre to be allowed to go to waste, especially as the reject flow is almost always at a slightly higher consistency than the inlet, so an essential feature of any screening system is the arrangement for treating the reject flow in some secondary screen. This has a vital role to play in determining the overall efficiency of the system and yet, as Steenberg has put it (4), 'Most manufacturers are happy to recommend other types of screen for the secondary stage, provided their own design is used for the first stage.'

Secondary screening equipment should be designed to cope with the lower flows and higher impurity concentrations involved. The lower capacity demanded generally necessitates the use of an entirely different
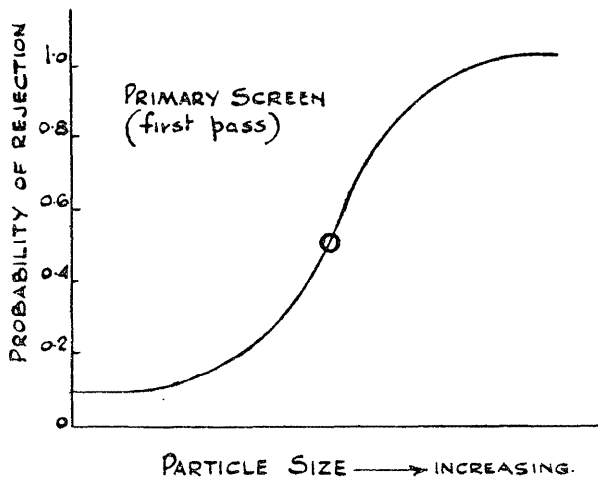
PARTICLE SIZE ———→ INCREASING.
FIG. 2.4a

Fig. 2.4. Effect on overall primary screen efficiency of using secondary screens of different efficiency

type of screen and it is unfortunately the case, as will be seen later, that the type commonly used for this purpose is excellent for fulfilling the duty of reclaiming fibre but only at the expense of having an extremely low efficiency of impurity removal.

Normally the secondary screen accept is returned to the main stock flow at a point ahead of the inlet to the primary screen. The efficiency of the secondary screen is thus highly important in determining the overall screening efficiency of the system. It is therefore interesting to examine the effect of different secondary screen efficiencies on the overall perform-ance. This is shown in Figs. 2.4a, b and c.

The primary screen is here assumed to have a typical relationship between the probability of rejection and the incoming particle size (Fig.

2.4a). This can be considered to apply for a first pass of stock containing an even distribution of particle sizes. The relationship between probability of rejection and incoming particle size in the secondary screen (Fig. 2.4b) is assumed to be higher in curve A, i.e. the efficiency of the secondary
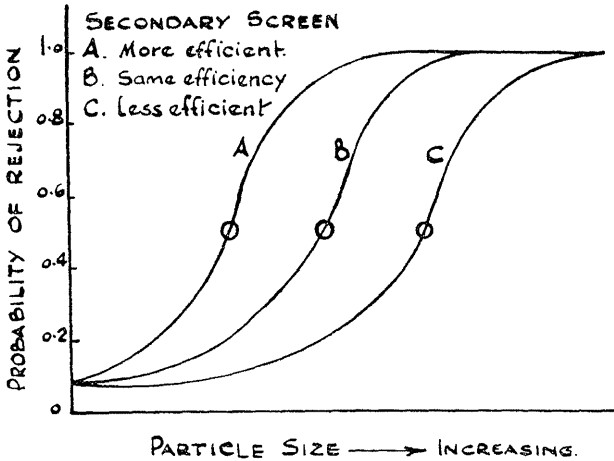
FIG. 2.4b
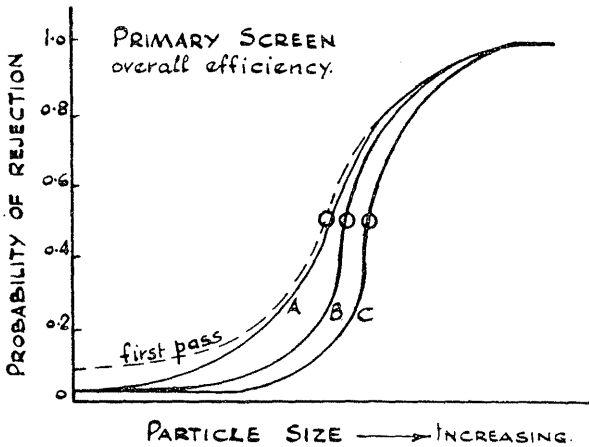
FIG. 2.4c

screen is greater than the primary, to be the same in curve B, and lower in curve C. The resulting effect on the overall efficiency of the primary screen when a secondary screen having these different efficiencies is added to the system is then illustrated in Fig. 2.4c, in which for comparison the original primary screen curve is shown dotted. (The overall probability of rejection for any given particle size can be readily shown to approach a value given

by the expression $ps/(1 - p + ps)$ where p, s are the probabilities of rejection in the primary and secondary screens, respectively). Reject flow is taken at 10 per cent. of the inlet in both screens and fibre reject from each system is the same, i.e. the efficiencies being considered are effectively those relative to fibre. The 50 per cent. probability points are marked with a circle.

These graphs show up several interesting points. Firstly, it is clear that however good the secondary screen efficiency, recirculating its accept to the primary screen inlet creates a reduction in the overall performance. This is particularly the case with smaller particle sizes where in fact little separation at all occurs and the probabilities of rejection are governed almost entirely by the split to accept and reject in volume flow from the system. For the larger particle sizes the efficiency of the primary screen largely determines the overall efficiency, but for particle sizes in between, the relative efficiency of the secondary screen obviously has a profound influence on the overall performance.

When a relatively high-efficiency secondary screen is used, curve A, the probability of rejection of large particles in the primary screen is hardly altered and the 50 per cent. probability size is only very slightly increased. This is certainly the most desirable state of affairs for screening because by this means fibre is saved for a negligible reduction in the efficiency with which the primary screen removes larger sizes of impurity. In this respect it is interesting to note that Tirado (24), in one of the few attempts to analyse this problem, advocated that the hole size of a secondary screen should be equal to the maximum *width* of impurity acceptable whereas the primary screen hole size should equal the maximum *length* of impurity acceptable. This could well provide a useful guide for laying down screening equipment, since it ensures that the effective efficiency of the whole system is that of the primary screen, and the secondary screen only mars this efficiency to a minor degree.

Using a secondary screen of similar efficiency to the primary, curve B, causes a noticeable reduction in the probability of rejecting the larger sizes of particles, and with a poor secondary screen it is clear that the 50 per cent. probability point is moved to an appreciably higher size of particle. It is not possible to give quantitative values to these curves, which are purely for illustration. But they do emphasize the disadvantages of using secondary screens especially of the older type that often have an efficiency approaching virtually nil; their only purpose is then in fact to save fibre and, by returning to the primary screen inlet practically all the impurities originally separated out, a build-up in concentration occurs which eventually means that the impurities are taken into the accept flow. In this event only those particles for which the probability of rejection in the primary screen is almost 100 per cent. will be removed. This gives a sharp cut-off in particle size rejected, perhaps the only desirable result, but as it must occur at a level so high as to command near certainty of rejection it implies all but the largest particles will pass to the accept.

Efficient secondary screen operation is thus seen to be of great importance and a reasonable conclusion to draw is that the efficiency should be

at least equal to that of the primary unit. The performance of a typical secondary screen can often be improved by diluting the primary reject flow to a much lower consistency than the main inlet flow; this is generally a feasible proposition as the basic flow involved is small and the size of the secondary screen still need not be great. Backwater or whitewater is used for this purpose and the dilution can be direct into the primary reject flow or through sprays which assist in the secondary screen operation. But taken by and large it is probably fair to say that the vast majority of screening installations in paper mills are giving only a fraction of the performance they could if more attention were devoted to the design and operation of the secondary units.

2A.16 Treatment of secondary screen reject flow

The reject from a secondary screen may contain such a negligible quantity of useful fibre and a very high proportion of impurities that it is worthless and can be taken to drain. On the other hand an efficient secondary screen system could well require quite a high reject flow which of necessity carries with it too high a quantity of good fibre to waste. There are then various courses of action possible.

In the first place this secondary reject flow can be returned to an early part of the preparation system in the hope that passage through beaters or refiners will reduce the size of impurities to a level that can be accepted in the paper (this applies primarily to the fibrous impurities, which screens are more efficient at removing, not metallic for which other considerations, in particular that of wear on moving parts in the system, have to be taken into account). Before doing this it may be necessary to have a coarse screen that separates out really large impurities that could cause damage or are impossible to break down small enough, but this need involve only a negligible fibre loss. The ultimate effect of recirculating rejects must be to increase slightly the proportion of fine impurities in the sheet though, depending on the efficiency of the primary screen, removal of larger impurities should not be unduly affected. This is probably acceptable where the general appearance of cleanliness in a sheet is not so important compared to its ability to withstand some converting process such as printing in which weak points at the site of large shives in the web can cause breaks.

An alternative procedure possible in mills where several machines are running different grades is to use secondary screen reject from one machine on another making a very coarse grade. Where several machines are on similar grades it is possible to channel together all secondary screen rejects (possibly also including the rejects from cleaning systems) to a single tertiary screen. As the inlet flow involved will be quite small, even when diluted well down, this screen can be of a relatively fine hole size and operate in such a way as to allow a large residence time on the screen plate. In this way it should be possible to recover most of the good fibre with a high efficiency of separation.

Secondary screen rejects often contain high proportions of shives,

especially of course when groundwood is used in the furnish. This is one indication that a primary screen is working well because removal of shives, being basically a question of separation by size, is very much the function of a screening system. In appropriate cases, a secondary screen reject flow containing many shives could be returned to the pulping plant, or alternatively it could be treated either continuously or by batch in a special kind of defibrator designed to break up shives. In some cases adequate treatment may be possible in the normal beaters or refiners of the preparation plant, as mentioned above, though the danger here is that larger shives start appearing in the paper and to overcome this the beaterman is instructed to treat the stuff harder, a course which may not be appropriate for other reasons.

2A.17 Return of secondary screen accept flow

Normal screening procedure is to return the accept flow from a secondary screen to join the inlet flow to the primary screen. Addition can be either direct to the screen inlet, or to a convenient backwater pit at a point chosen to ensure the flow enters the mixing pump, or into the appropriate compartment of a mixing box. There is nothing to choose between these positions and in practice the one most convenient to suit the system is selected.

It is definitely not advisable to allow the secondary screen accept to join the accept stock from the primary screen. The reason for this has been most clearly enunciated by Steenberg and Almin (4, 5) in their analysis of the coupling of screens. Streams of different cleanliness, i.e. containing different ratios of impurities to fibre in the stock, should not be mixed if the best screening efficiency is desired. The inlet flow to the secondary screen has a much higher content of impurities than the primary screen inlet (since it carries all those rejected), hence when the efficiency of both screens is similar the secondary screen accept can be expected to contain about the same impurity content as the primary inlet and so this is the position to return it to. It is of course possible that the secondary screen is so efficient it produces an accept flow with as low a dirt concentration as the primary accept flow, but this contingency is so unlikely with present-day secondary screens as to be ignored.

Steenberg also pointed out there is no objection to mixing streams of different consistency, and in fact where applicable this is useful to minimize the overall water flow and, thereby, pumping costs of the system.

Where a screening system is too large for the stock flow there are two alternatives; either a proportion of the flow can be recirculated to fill the screen, or the screen can be reduced in capacity by blanking off appropriate portions. (If the secondary screen is over-capacity it may be possible to increase the primary reject.) In theory the preferable alternative will be the one that best adheres to the rule that only flows of similar cleanliness should be mixed. In practice, depending on the type of screening system involved, the alternative cheapest to run will be adopted, provided the cleanliness level in the paper is satisfactory.

Occasionally the efficiency of the secondary screen can be so low that when coupled with a barely adequate primary screen efficiency the level of impurity removal is unacceptable. Short of making a complete change in equipment there is one course which is sometimes advocated to help improve this situation, that is to return the whole secondary screen accept to the preparation system in the hope that further refining will reduce the size of the impurities to a more acceptable level. This is similar in principle to the re-treating of screen rejects earlier in the system as mentioned above, but an important difference arises due to the relatively large flow involved.

If the wet-end flow system, and particularly the reject flow from the primary screen, is stable in volume and consistency, then leading the secondary screen accept away from the machine system need have no deleterious effect on the stability of substance of the paper. But if flows are liable to fluctuate and consistencies to change, then removal from the wet-end of a fair proportion of the total fibre in circulation could create problems in substance variation and may not be desirable for this reason. It is particularly hazardous to attempt to re-route secondary screen accept flow from one position (say the primary screen inlet) to another (say returning to the preparation system) while the machine is running because it will be found that this operation causes a complete change to the substance. These and similar matters have already been discussed in more detail in 1A.2.

2A.2 THEORY OF CLEANING

Whereas the operation of a screen depends on separating particles of different size, cleaning equipment operates by separating particles of different specific gravity. Some overlapping of function inevitably occurs because heavier impurities will often also be large in size, but by and large the nature of particles separated in the two pieces of equipment is quite distinct. The normal screen will not remove small heavy impurities such as grit, coal, scale, rust, and sand, except insofar as there is some region in the screen where a natural settlement has the opportunity to collect a proportion of these particles. Similarly the normal cleaner will not remove large clumps of fibres and shive, undissolved pieces of broke, sawdust, sisal hairs, etc., except insofar as some of these naturally follow the flow to reject.

In this section the principles of separation by specific gravity are discussed first. Then, because cleaners of the cyclone type are always operated in several stages to reduce fibre loss, the theory of coupling these together is dealt with.

2A.2 1 Separation by specific gravity

Separation of particles in a fluid by specific gravity depends on two basic factors. The first is the application of external forces which have a different

effect on the fluid and on the particles, causing a relative motion between the two. With conventional cleaning equipment this is always achieved by constraining the fluid to rotate in a circular motion, thus applying centrifugal forces. The second factor is resistance to motion through the fluid which the particles experience. This is primarily dependent on shape, and the way this affects drag on the particle, but is also affected by whether the flow is streamline or turbulent.

Analysis in any particular situation of the relative motion of particles in a fluid can be extremely complicated, but as an example the equation which applies for spherical particles in a streamline flow under the influence of a simple centrifugal field is $u = v^2 (\rho_s - \rho) d^2/18vr$ where u is the relative velocity between particle and fluid in equilibrium conditions, v is the velocity of flow of the fluid in a circle radius r, ρ_s and ρ are respectively the densities of the particle and fluid, d the diameter of the particle, and v is the coefficient of viscosity of the fluid. This equation shows immediately why separation occurs in accordance with specific gravity for the greater the value of ρ_s, the higher is the value of u. Size of the particle is also important, for the relative velocity u increases in proportion to d^2, effectively the cross-sectional area of the particle.

Two other points are worth noting from this equation. Firstly, the separation effect is proportional to v^2, the square of the velocity of the fluid. This shows up the tremendous advantage of high velocity of circulation and explains why greater inlet pressure to a cleaner always brings about an improvement in performance. Secondly, the separation effect increases when the fluid flows in a circle of smaller radius, r. This means that, other things being equal and in particular velocity being maintained, the smaller the diameter of the walls constraining the fluid into a circular motion the better. Hence the reason why smaller diameter cyclone cleaners are more efficient. It may be observed further that an increase in viscosity, v, of the carrying fluid decreases the separation effect; in practice this becomes relevant as consistency increases. Practical examples illustrating these points will be given in **2A.24** and **2B.65**.

It is not difficult to arrange for fluid to be constrained to flow in a circle. All that is required is a container constructed with cylindrical symmetry in order to promote rotation; the force of this rotation is then encouraged by injecting the flow at a tangent to the outer wall. Older types of cleaner worked on a different principle which involved rotating the whole outer wall to impart rotation to the fluid, but the inadequacies of this from a constructional point of view are fairly self-evident and here attention is confined essentially to the type of cleaner that depends for its operation only on force induced by inlet pressure on the fluid.

Fluid injected into a cylindrically-shaped container in this way can readily be drawn off at a point near the axis, leaving a small reject flow to carry off heavier particles concentrated against the outer wall to which they are thrown in accordance with the principle discussed above. There must be an inward flow of fluid from the tangential inlet close to the outer wall towards the central axis where it leaves the container; for a particle to travel outwards to the outer wall the relative velocity (u in the

equation) must exceed this natural inward velocity of the fluid. The typical fluid flow in a cleaner is shown in Fig. 2.5.

2A.2 2 Type of vortex

The important question with the flow in any cylindrically-shaped container is, what is the relationship at various points within the container between the velocity in the direction of rotation (inward and axial motion are
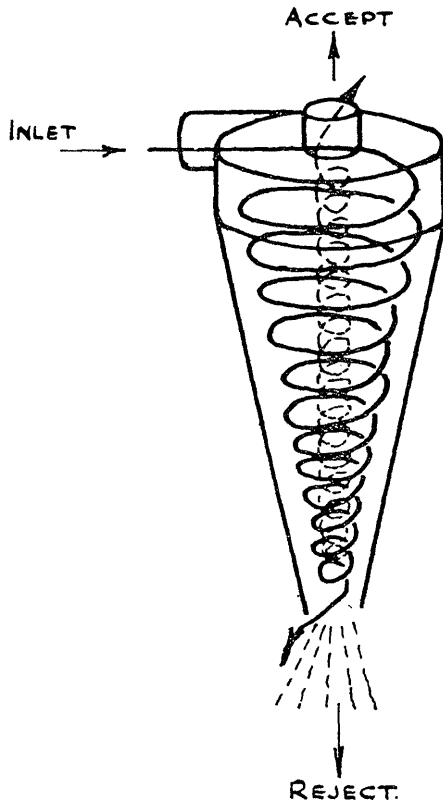
Fig. 2.5. Illustration of the main flow in a typical cylindrically-symmetrical cleaner

generally relatively small) and the distance from the central axis, in other words between v and r in the equation quoted above. This is particularly vital because the separating effect has been seen to be proportional to v^2/r. If, as the fluid flows inward from the wall and r decreases, the velocity v increases as well, then it is evident that v^2/r increases so the effect of centrifugal force builds up as the flow passes inwards and the separating effect increases. But if on the other hand v decreases as the central axis is

approached, it may be that v^2/r, and therefore the separating effect, actually diminishes. The result of this would be that unless a particle were subjected to sufficient centrifugal force immediately on entering for it to receive an impetus starting it towards the outer wall, the opportunity to avoid being drawn into the accept flow would be passed as thereafter the centrifugal force would diminish.

These two extremes are met in practice in the form of what are known as an open or free vortex, and a closed or forced vortex. In the free vortex the velocity v is inversely proportional to the radius r, i.e. $v = k/r$, k constant; in other words angular momentum is conserved and the fluid rotates faster and faster the nearer it gets to the centre. The separating effect in this case is proportional to $1/r^3$, and so increases tremendously as r decreases. In the forced vortex fluid rotation is like a solid and the velocity v is directly proportional to the radius r, $v = kr$. Here the separating effect is proportional to r which implies that a decrease in r reduces its strength.

It is evident that it is more desirable for flow in a cleaner to take the form of a free vortex than a forced, and fortunately fluid has a natural tendency to form a free vortex. In practice the flow falls somewhere between the two, because the free vortex is modified by several factors such as inner friction and viscosity, the drag of the containing wall, and lack of complete smoothness in the flow. If the general relationship between v and r is expressed as $vr^n =$ constant ($n = + 1$ free, $- 1$ forced vortex) then as an example it may be mentioned that various workers have estimated n at between 0.5 and 0.8 in cyclone cleaners. But in fact n appears to be dependent on r in such a way that there is a transition from a more free vortex near the wall to almost a forced vortex at the centre along the cyclone axis. The whole matter is thus rather complicated.

2A.23 Secondary flows

So far attention has been confined to the circular or tangential motion which is the predominating one in any cylindrically-shaped cleaner. But in addition to this there are two other important secondary motions and it is upon these that much of the efficiency of a cleaner depends. These secondary motions are essentially a function of the geometry of the cleaner and both affect the initial separation induced by centrifugal force.

The basic problem is to arrange for all the heavy impurities thrown to the outer wall of a cleaner to go one way, and all the fibre to go another. Usually this is solved by using an orifice sited in the top of the container over the central axis for removal of the accept flow, and a second orifice at the bottom, which is either also concentric with the axis or tangential to the wall, for removing the reject flow. Direct flow from inlet to accept is generally minimized by some form of cover or 'vortex finder' round the accept orifice. The reject flow can be direct from the bottom of a cone (as in a cyclone cleaner) or from a specially designed baffle arrangement; in some cleaners the reject flow is to a fixed vessel which gradually accumulates rejected material, but more commonly, at least in a primary cleaning stage, there is continuous evacuation.

The main secondary flow brings about this separation to accept and reject; for a cyclone cleaner it is shown in Fig. 2.6 (i). The reject flow is almost entirely from the boundary layer close to the wall, a comparatively slow-moving downward flow which retains the larger impurities thrown into it. Any disturbance to the smoothness of this flow (such as would be caused by undue roughness of the wall) induces impurities to be swept upwards into the accept flow. In some models of cyclone, elutriation water
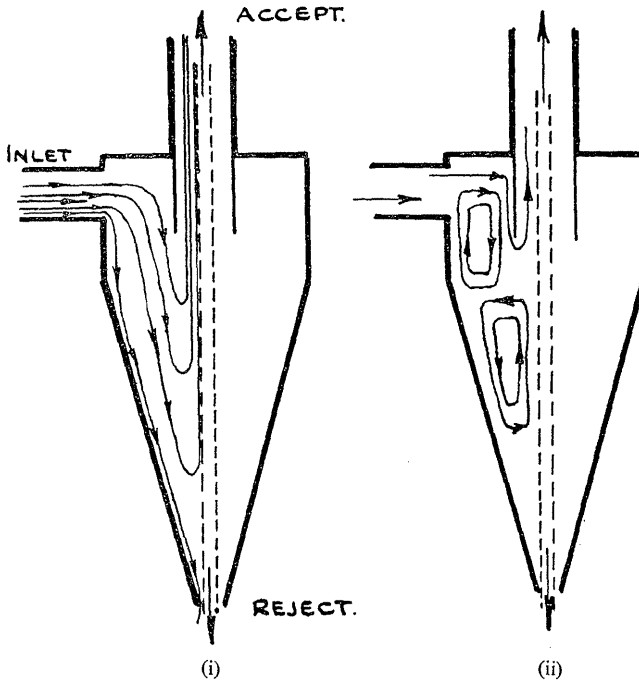
Fig. 2.6. Diagram illustrating secondary flows in a cyclone cleaner: (i) separating accept and reject; (ii) double-eddy motion

is injected tangentially near the apex of the cone to dilute the flow and reduce fibre rejected; there must be a distinct danger in this of disturbing the smooth flow of impurities down the wall unless the velocity of entry is carefully matched to the natural rotational velocity in the cyclone at that point.

Superimposed on this essential secondary flow is another which can take various forms depending on the shape and design of the cleaner. This flow is invariably deleterious to cleaner operation because it spoils the straightforward tangential spin and separation of accept and reject flows which set the main level of efficiency. Unfortunately little is known about the form this flow can take except that it is difficult to prevent;

baffles placed inside the cleaner to reduce its intensity invariably seem to have the opposite effect. To the author's knowledge a thorough investigation has only been made for the cyclone cleaner where optical observations of aluminium and perspex spheres flowing in water through a glass cyclone first brought the existence of this particular secondary flow to light.

The form this takes in a cyclone is shown in Fig. 2.6 (ii). There is first of all a direct flow from the inlet down the side of the vortex finder surrounding the accept and straight into the accept flow. This is a particular source of inefficiency because in this region hardly any separation occurs at all. The other flow is a double-eddy motion which is probably closely related to the cyclone shape and can be expected to take a completely different form in a wholly cylindrical cleaner. This double-eddy, apart from being wasteful in energy, is also undoubtedly a source of inefficiency because it disturbs the cleanness of separation to the accept and reject in the main flow.

Another feature of the flow which has been observed in cyclone cleaners, and may also be present in other types if the spin is strong enough, is a central column free of water (this is shown dotted in Fig. 2.6). This column is effectively at zero static pressure and is of a diameter which is dependent on the size of the accept and reject orifices. It does not contribute in any way to the efficiency of separation in a cyclone, being purely a result of the extremely high velocities reached near the axis. But unfortunately, being at near zero pressure, an insuction of air takes place into this column when the reject orifice is open to atmosphere. This adds to the free air in the flow, presenting in the case of paper stock an undesirable feature. On the other hand, the existence of the low-pressure column can also be expected to cause air already in the inlet flow in a free form to boil out. Efficient removal of air from this column can thus be expected not only to prevent insuction but to reduce to some extent the free air already in the flow. This will be discussed more fully in 2B.63.

2A.2 4 Examples of separation achieved

Most investigations into the operation of cleaning equipment have been with the cyclone type, and some of the results obtained will now be presented to illustrate the effect of varying conditions. The purpose of this is to show the practical effect of those changes considered earlier from the purely theoretical standpoint. The basis of comparison is the percentage of particles in the inlet that pass out in the reject. This is analogous to the probability of rejection in screening equipment and it will be noted that there is a basic similarity to the shape of curves presented in Figs. 2.3 and 2.4.

Fig. 2.7 shows the typical effect on efficiency of rejection with increasing particle size for three different sizes of cyclone cleaner. The curves relate to spherical-shaped, heavy particles. The relatively rapid increase from a minimum level of rejection for very small particles (determined by the

volume percentage of flow in the reject) up to 100 per cent. removal indicates the relatively sharp cut-off in size which occurs, an advantageous feature of cyclone cleaners. The reason for this is partly the relatively efficient nature of the separating flow in a cyclone and partly the dependence of the separating effect on the square of the particle diameter, as discussed in **2A.2 1.**

Increasing the diameter of the cyclone with other conditions constant, in particular pressure at the inlet, reduces the efficiency of the cyclone for all levels of particle size. The effect is quite marked and has been confirmed in countless different experiments. It results entirely from the fact
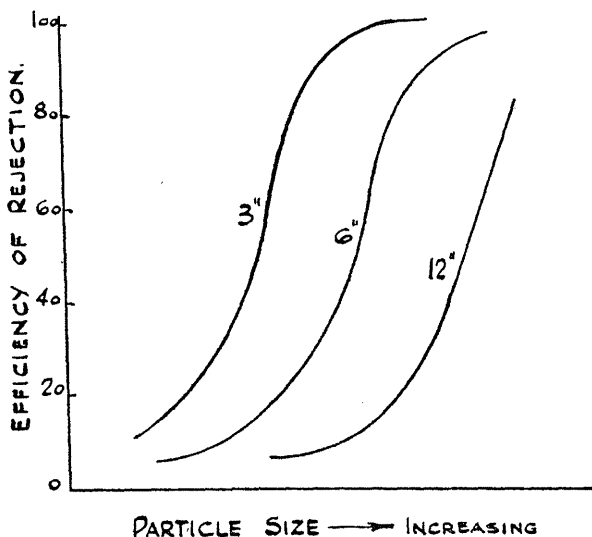
Fig. 2.7. Effect on efficiency of rejection of near-spherical particles in different diameters of cyclone cleaner

that, though velocity at the cyclone wall is the same in the larger cyclone for equal pressure at the inlet, the radius of rotation is larger and this reduces the separating effect proportionally.

The effect of increasing specific gravity (not shown) is to shift the whole curve to the left. Grit and iron particles are rejected more efficiently than ash and sand of the same size because the latter have lower specific gravity.

Fig. **2.8** shows a different aspect on the rejection efficiency of cyclone separation, the effect of particle shape. If instead of being near-spherical, particles are of a flattened shape, then the curious effect illustrated occurs; increasing overall size of the particle leads first to a normal increase in rejection efficiency but then to a sudden tapering off and fairly rapid decrease in efficiency. The precise reason why this occurs is unknown, though since particle shape has a close influence on the drag coefficient it is hardly surprising that the curve is different from that for spherical

particles. But exactly why a higher proportion of large flat particles pass through to the accept has not yet been explained.

The fact that it happens, however, is highly important when the rejection of shive-like material is considered, especially as this effect is very pronounced for material with as low a specific gravity as shives. Brecht (19) has estimated that it applies very strongly when the ratio of cross-section length to thickness exceeds about six to one, while Kemp and Rance (26) have put it at about five to one. Fibres of course exceed this ratio, which
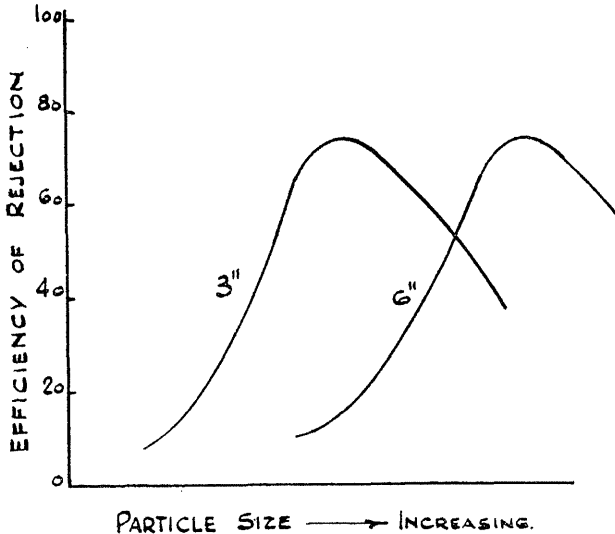
Fig. 2.8. Effect on efficiency of rejection for flat particles of different sizes

is perhaps a fortunate reason why a higher percentage of these do not appear in the reject; in this respect it is interesting to note that those fibres found in the last stage of a typical cyclone system do tend to be short and fine rather than long, a confirmation of the effect of particle shape. This topic will be returned to in 2B.6.

2A.2 5 Coupling of cyclones together

With many types of cleaner it is customary to utilize as a secondary stage a specially-designed low capacity model similar to but smaller than those used in the primary stage. In this case the same general principles apply as for screens where it was seen that a secondary unit should be at least as efficient as the primary if overall performance is not to be severely prejudiced.

With the cyclone cleaner it is more common for the same size to be used throughout and as a consequence three and even four stages of reject treatment may be needed to reduce the final fibre loss to an acceptable

124

degree. Although at first sight this appears to lead to a cumbersome arrangement, it does ensure that there is no marked decrease in efficiency of the secondary and later units. The whole problem of how such large numbers of individual units are to be coupled together is then very important. This will now be discussed; the information presented has been drawn from theoretical discussions presented by Steenberg and Almin (4, 5), Nuttall and Hendry (18), Brecht *et al.* (19), and Corte (20).

In the first place, the capacity of an individual cyclone unit is relatively small and to cope with the sort of flows common to paper machine stock systems a large number linked in parallel are needed. For the purposes of discussion such an arrangement can be considered equivalent to a single treatment of stock with a common inlet, accept, and reject flow. The primary accept flow could be led to a further unit of cyclones to establish an even greater degree of cleanliness, but the author has heard of no mill where this has in fact been done, presumably because of the heavy pumping costs involved in double treatment. So effectively the most important consideration is the manner of dealing with the reject flow. This is done in what are commonly called a series of 'stages'.

The reject flow from the primary or first stage of cyclones should be taken direct, after appropriate dilution (see next section) to the second stage; the accept from the second stage is then returned to join the untreated stock in the first stage inlet. The reject flow from the second stage may contain a small enough quantity of fibre to be manageable, but normally the same treatment is repeated in a third stage. In this case the accept flow should return to the inlet of the second stage. Further stages can be added and in each case the accept flow should return to the inlet of the previous stage. The resulting arrangement is illustrated in Fig. 2.9 and this has been shown to be the most economic in terms of securing minimum pumping costs and low fibre loss from the final stage.

It would appear at first sight that the addition of successive stages should reduce the fibre loss from the final stage reject to as small as desired. Although re-treatment of reject flows in a further stage after the second does affect the overall efficiency of impurity removal (just as was seen from the case when a secondary screen is introduced) Nuttall and Hendry have shown that when the efficiency of a single pass is high, as it is for heavier and larger dirt particles passing through cyclones, then the change in efficiency of the whole system resulting from addition of a third or fourth stage is in fact so small as to be negligible. This applies even if the efficiency of the final stage is reduced considerably to minimize fibre loss, e.g. by using elutriation water or an enclosed reject collecting chamber. As an example, their work indicates that even if the third stage of a cyclone system has only 30 per cent. efficiency instead of 90 per cent. as in the first stage, the overall efficiency in terms of impurity removal relative to fibre in the primary accept drops from only 88·9 per cent. to 86·6 per cent.

But treatment of rejects in too many stages is not practicable for two main reasons. Firstly a certain flow is required to fill a single cyclone at normal inlet pressure, so the size of the final stage is limited. It would,

of course, be possible by diluting successive reject flows more and more to keep adding cyclones in stages. But when this is done it is found that the actual reduction in fibre loss taking place becomes less and less because beyond a certain point the more stock is diluted the greater is the percentage loss of fibre (see Fig. 2.17 on page 166).

The second reason that the number of reject stages has to be limited is due to the selective rejection of shorter fibres and fines that occurs.
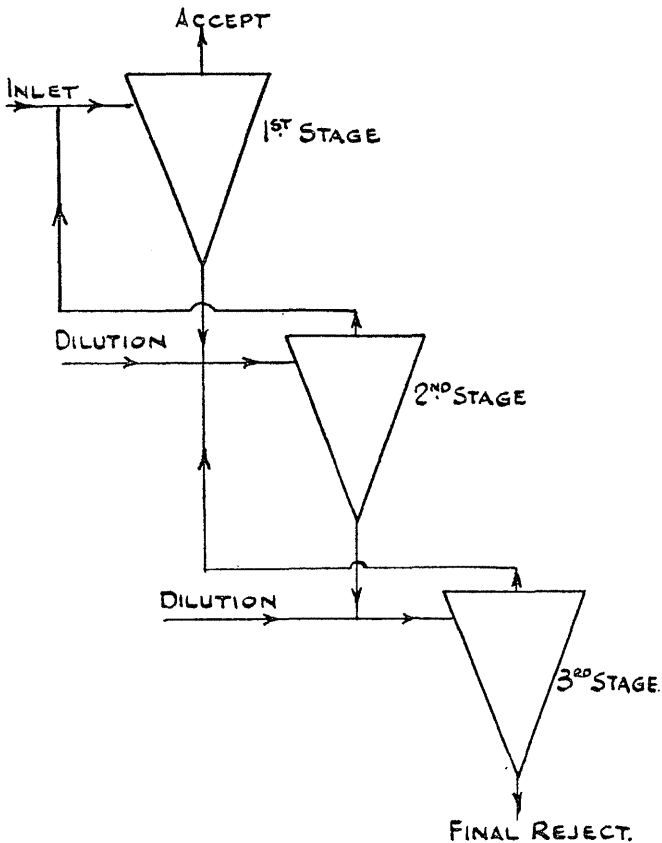
Fig. 2.9. Arrangement of cyclones in a three-stage system

This has the effect of increasing the percentage loss of fibre in successive stages, even when the inlet consistency and the percentage volume flow to the reject are unchanged; in other words the ratio of the reject consistency to the inlet consistency, the 'thickening factor', increases. For example, for an inlet consistency of 0·8 per cent. in each stage, the reject consistency of the first stage might be 1·6 per cent., of the second 3·0 per cent., and

of the third stage 4·5 per cent. This increase in thickening factor thus diminishes more and more the advantage in reducing fibre loss gained by adding a further stage.

For these reasons the number of stages usual in a system of cyclones is normally three and only very occasionally four. Even then as much as 50 per cent. of the fibre entering the final stage can be rejected. To add a further stage would cause so little further reduction in fibre loss that the added capital cost and increase in pumping costs (an extra pump always being necessary for each stage) cannot generally be justified.

2A.2 6 Planning a cyclone installation

The arrangement of a system of cyclones into an appropriate number of stages requires careful planning to determine how many units are needed in each stage and the number of stages it will be economical to use. The inlet pressure for running must first be decided on the basis of power cost versus efficiency for the first stage (see 2B.6 5), and from this the rated throughput of a single cyclone under normal operating conditions can be obtained from the manufacturer's specification.

Next it is necessary to have some idea of the percentage of flow which will go to the reject. This depends entirely on the size of the reject orifice, the vacuum applied if any, and whether there is any restriction to the accept or reject flow. There is always a minimum reject size below which operation of individual cyclones is not smooth, either because the flow becomes uneven or erratic or because the hole is so small that it gets partially or wholly blocked too easily. When planning an installation care is taken to assume a reject flow appreciably larger than this minimum because even if the cyclones are set up initially with the reject orifice diameter at the minimum tolerable, as wear of the cyclone body occurs the reject widens giving a higher flow. In this respect it is worth noting that any cyclone works most efficiently, i.e. with minimum impurities to fibre in the accept flow, when the reject diameter is as small as practicable. So as reject orifices widen a cyclone system becomes less efficient, largely because of the greater fibre loss resulting from the final stage. It is therefore wise to avoid planning an installation that will be able to cope with very large reject flows lest the gradual increase in fibre loss over a long period goes unnoticed.

Finally, the likely degrees of thickening in successive stages must be known or estimated for the average reject diameter it is intended to use. If no comparable furnish has been treated before, experimental work may be needed to obtain reliable enough information on this point. But nowadays most manufacturers have sufficient data for an adequate range of furnishes and beating treatments to make this unnecessary.

With all this information the numbers of cyclone units in each stage and the number of economic stages can be determined, though the task is not easy to do well. Even the expert generally relies on trial and error though formulae have been developed by Nuttall and Hendry which enable the job to be done systematically. Addition of dilution water

(usually from the machine pit) is necessary for each stage but the first one to keep the inlet consistency down to a level where efficient separation occurs; this is normally arranged so that inlet consistency is about the same or lower in each stage, allowance being made of course for the consistency of the dilution water which can be high with furnishes containing short fibres and loadings. Fortunately, though calculation of the numbers of cyclone units in this way is necessarily approximate, there is considerable latitude in practice because more or less dilution water can always be added in any stage to adjust the flow to suit the number of cyclones. But reasonably accurate determination is still desirable otherwise each stage will be installed oversize and in operation one or more units may have to be blocked off and the pump run at an inefficient level of efficiency.

The capacity required in the first stage depends on the flow of stock to the breast box and the amount recirculated from the other stages. Both are subject to much error in measurement or calculation and it frequently happens that the capacity well exceeds the actual flow to be treated. To keep the cyclone units full and working efficiently, it is then necessary either to block off a sufficient number of units to obtain a reasonable inlet pressure, or to recirculate a proportion of the flow. The more appropriate course depends on the demands of cleanliness for the paper: recirculating increases the quantity of impurities removed, but also increases the percentage of fibre lost from the final stage. According to Nuttall and Hendry this occurs in such a way that if a proportion p of the accept flow is recycled, the impurity content decreases by a factor $(1 - p)$ but the fibre reject increases in proportion to $1/(1 - p)$. Also pumping costs increase with recirculation, certainly when a variable-speed pump motor is used for the first stage; even when the flow is simply controlled by a valve on the discharge of a fixed speed pump the pumping costs can also increase with recirculation depending on whereabouts on the pump characteristic curves the running conditions fall.

Occasionally the cyclone installation is installed in the flow system with a separate pump to the main mixing pump. This has the advantage that power is not consumed if at any time it is possible to run the machine without the cleaners operating. When there is some sort of buffer between the two pumps, a separate chest or some other piece of equipment such as a level-controlled deculator, this procedure is perfectly satisfactory and gives a more flexible system. But on the other hand with a completely closed system, operation of two pumps in series can present certain complications, especially with regard to stability, and automatic control of the flow to the breast box is then advisable.

2A.27 Minimizing fibre loss

It is possible to re-use fibre from the final stage of a system of cyclones in one of a number of ways similar to those described for treating screen rejects. This is not normally done, however, because it is found in practice that the proportion of impurities to fibre in a final stage is so high that

re-use is never contemplated. Furthermore, the fibre that is present is generally very short and of low brightness, and the impurities often of a highly abrasive type which would create rapid wear if they were recirculated to an earlier part of the system and allowed to build up. Because of this it is all the more important to plan a cyclone installation to have as low a fibre loss as possible.

Ways of achieving this have already been described and in particular the limitations of adding more than three or four stages have been explained. Fibre loss can still even in a well-planned installation amount to 1 per cent. or more of fibre passing through the installation, which means an even higher percentage loss when this is expressed in terms of production (because a proportion of fibre passing through the installation comes from the backwater). So other methods of fibre loss reduction have been sought. Most of them depend on using a different or a modified cyclone unit or units for the final stage. These modifications, discussed in **2B.6 3**, sometimes take the form of adding elutriation water close to the reject orifice to reduce consistency there, or they can involve a smaller cyclone or one with some special arrangement on the reject which allows the fibre loss to be controlled.

Any of these modifications invariably not only reduces fibre rejected but also to some extent the efficiency of impurity removal. It is rarely possible to do the one without the other. However, it has already been seen that the efficiency of a final stage can be reduced appreciably without materially reducing the cleanliness of the main stock accept. So provided adaptations to the final stage are not noticeable in terms of increasing impurities in the paper, and this should normally be the case, then any course of action along these lines is to be recommended.

One suggestion put forward by Nuttall and Hendry is that a proportion of the final reject should be returned to the inlet of the final stage. Where capacity of the final stage allows this, and the resulting increase in thickening factor does not offset the effect as eventually it will do if too much is recycled in this way, then this seems to be a satisfactory and simple means of achieving a reduction in fibre loss. If a proportion p of the final stage reject is recirculated direct to the final stage inlet, then a reduction approximately proportional to $(1 - p)$ in the fibre loss can be expected for negligible change to the overall dirt removal efficiency of the system.

2A.3 ASSESSING SCREEN AND CLEANER EFFICIENCY

In the preceding discussion of screens and cleaners, a great deal was said about the 'efficiency' with which particles are rejected. This is a simple term to use, but it can be interpreted in several ways. When new screening or cleaning equipment is installed it is natural to expect some assessment of its 'efficiency' to be made, if only to ensure it is operating satisfactorily. How to do this in practice requires about the most painstaking experiment that a mill laboratory is likely to undertake. This section is devoted to a few notes on this whole question of efficiency, how it should be defined, and how it can be measured.

2A.3 1 Definitions of efficiency

The difficulty about finding a satisfactory definition of efficiency is that the performance of any screen or cleaner depends not only on how well it operates in different conditions, which is what is of most interest, but that it depends also on the type of impurity concerned. To be clear about this, consider first the curves in Figs. 2.3 and 2.7 which show, for a screen and a cleaner respectively, how the probability or efficiency with which a particle passes out in the reject flow depends closely on the size of the particle. A really comprehensive assessment of efficiency demands a series of curves of this type covering different specific gravities and operating conditions.

This would be time-consuming and in most cases unnecessary because the curves would all be similar. There are exceptions, as for example with cyclone cleaners when the shape of a particle strongly influences the curve. In this case a full assessment over a range of particle sizes is vital. But otherwise from typical curves a number of parameters may be used with which it is possible to extrapolate to other conditions without actually performing the tests. These parameters are useful, especially for comparing different types of equipment.

Most common of the parameters in use is the size of particle which has an even or 50 per cent. chance of leaving in the reject flow. As an alternative, where particles of the same size but differing specific gravity are considered, the specific gravity with a 50 per cent. chance of rejection can be taken, but this cannot sensibly be applied to screens where specific gravity has little influence on separation. An alternative and less easily defined parameter is to take the largest size of particle within some common grouping (for example between standard mesh sizes) which appears in the accept flow, i.e. the largest size of particle which falls below 100 per cent. reject efficiency.

Each of these parameters have their place, the 50 per cent. ones being particularly useful for comparing performance. The maximum size of impurity appearing in the accept is of importance for certain specific papers, e.g. photographic base, and also from a purely visual standpoint since a single large speck of dirt is far more readily noticed than a number of smaller specks of equivalent total size. A simplification of this parameter is to consider only the efficiency with which particles over a given size are rejected. This too has a strong practical justification and can be related to visual terms or to such things as the likelihood of causing a break on the machine. It is certainly the easiest to assess, and probably for this reason is a common one to use.

An equally important aspect of efficiency is the sharpness with which separation occurs. A screen or cleaner which gives a very gradual increase in probability of rejection as particle size increases, curve A in Fig. 2.10, will generally be less desirable than one with a very sharp cut-off, curve B, even though the cut-off occurs at a relatively large size. This is because it is frequently more valuable to be certain of excluding impurities above a certain size than to remove a higher percentage of smaller particles,

an extension of the point made in the previous paragraph. The difficulty here is that the 50 per cent. probability size as a measure of rejection efficiency is inadequate, as comparison of the two curves A and B shows: the 50 per cent. particle size is in fact smaller for A than B and so the former might be thought the better though in practice the latter is almost always preferable. This is one argument for preferring the definition of efficiency as maximum size in the accept, and for the same reason the simpler definition using rejection of some relatively large standard size of particle is also satisfactory.

These then are some definitions of efficiency which are perfectly adequate as they stand for assessing the removal of particles to the reject. But for
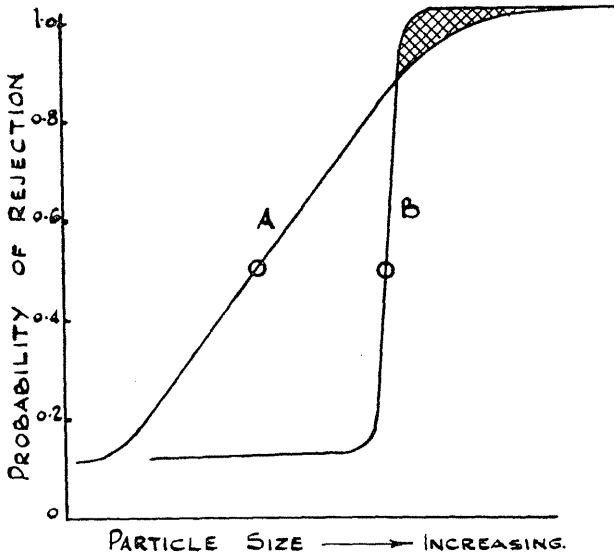
Fig. 2.10. Curves relating probability of rejection to particle size for equipment with a poor (A) and a sharp (B) cut-off. Curve B will usually be preferable because it is more efficient in removing the large particles in the shaded portion

papermaking what is important is the rate of removal *relative to fibre*. The efficiency of a cyclone cleaner, defined in any of the terms above, can be made to increase simply by opening up the reject orifice, which of course causes the quantity of fibre rejected to increase also. There will then be a lower number of particles of any particular size passing in a given time to the accept, i.e. a higher absolute efficiency of rejection, but relative to the quantity of fibre in the accept (and hence to area of paper) there may well be more particles and hence true efficiency will be lower.

The point here is that the efficiency of rejecting particles, however measured, must take account of the quantity of fibre in the reject. If the

131

latter is always kept the same, or effectively the same as when the reject volume is kept constant though small changes in consistency may occur under different conditions, then efficiencies of particle rejection can be compared directly. Otherwise a correction is necessary and this amounts to defining efficiency as (reject per cent. of impurity − reject per cent. of fibre) × 100/ (100 − reject per cent. of fibre).

Alternatively, when the method of assessing efficiency is defined in terms of the number of particles above a particular size, then for the same inlet conditions a direct comparison can be made of the actual numbers occurring in a fixed volume of accept flow provided each figure is multiplied by a correction factor which allows for any difference in the actual flow rate of fibre in the accept as determined from flow and consistency measurements.

2A.3 2 Measuring rejection efficiency

There have been surprisingly few reports giving details of experimental as opposed to general machine tests of screens and cleaners, and most of these have referred to cyclone cleaners. This is unfortunate because reliable data is so hard to obtain from equipment in mill operation and it is rarely practicable to investigate the effect of changing operating conditions. Above all the opportunity of adding a controlled type of impurity to obtain a really accurate measure of rejection efficiency is not possible in a mill installation.

For any sort of development work and for comparing the efficiency of a particular screen and cleaner at different operating pressures, consistency hole size, and so on, it is essential to be able to detect and measure some representative type of impurity when it is mixed in with the normal paper stock. Various techniques have been devized for this, including the dyeing of sawdust to represent shive-like particles, radioactive tagging of shives, adding sand to the stock, or adding various other readily recognized dirt particles. Counts on a suitable number of handsheets, together with measurement of flows and consistency for the inlet and reject are then adequate for determination of fibre and impurity reject percentages; the usual difficulties of dirt counting need not apply in experimental work of this nature since the size of impurity and its identification are chosen to minimize complications. In the case of sand or loadings, ashing the handsheets gives a convenient measure of the quantity of impurities in any flow.

Normally, however, such tests are outside the range of a mill where deliberate contamination of stock, particularly in a form that is readily identified, is out of the question. It is sometimes possible to make sense out of dirt counts done on handsheets made from stock sampled from relevant points of the system, but the difficulties are phenomenal. Use of the modified TAPPI dirt chart is helpful in reducing operator errors in dirt counting and for checking different size groups of impurity, but generally it is found that far too many counts are needed to obtain reliable figures and a count on the same sheets can vary enormously from one

operator to another. An alternative is to compare handsheets with a standard set of carefully protected sheets containing various degrees of dirt of the kind normally encountered in the grade of paper concerned, but this allows only a general assessment applicable to the range of dirt present in the system at any particular time and at best can give only a rough comparison.

2A.3 3 Assessing the worth of a mill installation

A mill installing new screening or cleaning equipment is primarily interested in knowing if the money has been well spent. It is not adequate simply to examine rejects for the type of impurity present because this is notoriously unreliable, depending as it does on the amount of dirt in the stock system at the time of examination (and this obviously can fluctuate from day to day) and on the amount of fibre associated in the reject with the impurities. A comparison over a long period is essential and this can be done in several ways.

Firstly samples of the actual paper produced can be examined and a direct comparison made of the dirt content before and after installation. Provided the installation does not coincide with some marked seasonal change in the amount of impurities present, e.g. in pulp, slime, etc., a reasonably reliable picture should emerge in a relatively short time if any significant improvement has occurred. Sheets for this purpose must be carefully protected in plastic bags, and counted at the same time in randomized order to eliminate bias. A development of this approach is to use a laboratory dirt counter such as the PAPRIC or even a dirt counter on the machine. Provided the limitations of these instruments are accepted, they can provide a more objective evaluation particularly in the case of a laboratory tester where sheets obtained over a period can be tested one after the other and instrument and operator error thereby minimized.

A less rigorous comparison is sometimes possible simply by comparing the number of breaks occurring or reels rejected due to dirt and allied causes such as blotches in the web. Similarly, sheets rejected for dirtiness in the salle or on a cutter with an electronic dirt-detection sorter can be used. With new cleaning equipment when improved separation of abrasive particles in pulp and loadings is expected, comparison of wire life and of the period between grinding of calender rolls can provide a useful indication of improved efficiency.

Shive removal is particularly important in some grades and determination of this is very difficult. Counting handsheets is especially hopeless when dealing with shives and other methods have been proposed. One is to screen samples from inlet and reject in a Bauer McNett fractionator, taking the weight of the fraction greater than 14 mesh as representative of the quantity of objectionable shives present (though it necessarily also contains fibre). Another similar method is the British Standard using the Sommerville fractionator. A third that has been reported is to use a mesh of 5 to the inch in a flat screen under standard conditions, continuing the screening to exhaustion and collecting the rejects for weighing. Unfortunately, as Robinson and Kingsnorth (29) have reported, these various

methods often give contradictory results due to differences in the type of shive separated out. A careful comparison by Macmillan *et al.* (35) has confirmed that counting or weighing techniques for assessing shives in newsprint are unreliable. These workers also reported that other attempts relying on detection of shives by measuring gloss or using X-rays and monochromatic light of various wave-lengths including ultra-violet gave no marked contrast between shives and fibre; the conclusion reached was that as yet there was no really satisfactory means of assessing shive content accurately and in particular neither the 14 mesh retained-fibre in the Bauer McNett nor the flat screen technique appeared much use because too many shives which could in practice be troublesome passed through.

The most suitable method of assessment also depends on the size of the shive that it is thought necessary or desirable to remove. In respect of printing papers it is worth noting the work that has been done by Hopkins (32), Macmillan (35), and Sears (36), and their respective colleagues. Their reports show conclusively that shives are a major source of web breaks in newsprint and the likelihood of a break is greater the larger the size of shive. Such breaks can occur at tensions well below the average tensile strength of the paper because a long, thin shive, particularly one set in the cross-direction, provides a weakness due to the poor bonding of fibres on to its surface.

To obtain concrete data on the size of shive responsible, a means of assessing the 'runability' of the paper is needed and various types of simulation tests have been tried. Running at high tension on a winder was used by Hopkins *et al.* as a simple test for this purpose and they found that 50 per cent. of breaks occurring were attributable to groundwood particles of 1·5 sq. mm. or larger in area and 90 per cent. to particles 0·7 sq. mm. or more in area. Following a different approach Sears *et al.* developed an instrument for subjecting a 16 in. reel of paper to increasing strain and showed by this means the extent to which shives can be responsible for breaks (of 3,200 breaks, all but 45 had the fracture passing through one or more shives); this work indicated that most of the shives responsible were over about 3·5 to 4 mm. in length and of a width up to half the thickness of the paper. The importance of this line of research to newsprint and similar grades is very evident and more reports on this subject can be expected.

CHAPTER 2B

OPERATING FACTORS AFFECTING SCREENS AND CLEANERS

2B.1 POSITION IN THE FLOW SYSTEM

For discussion of operating factors affecting screens and cleaners it will be convenient to differentiate between the main groups of equipment available and treat each in a separate section. This course is adopted because the behaviour of screening and cleaning devices is invariably individual to the particular operating principle involved, and the effect on performance of variables such as stock consistency, stock flow, impurities in the stock, and so on is in turn largely dependent on the particular model concerned.

First, however, there are several general points concerning screens and cleaners that are relevant whatever the models concerned. These relate to the method of feeding stock to a unit and dealing with the accept and reject flows, and also to the question of where in the wet-end flow system, and in what order, screens and cleaners should be used. These subjects will now be considered.

2B.1 1 Position of screening and cleaning equipment

It is common practice when applying screens and cleaners to the treatment of paper stock to choose a position in the wet-end flow system between the mixing box or pump and the breast box. There are two reasons for this. Firstly, in this position the consistency of the stock after dilution with backwater is generally under 1 per cent., and it is only possible to remove relatively small impurities at a consistency as low as this. Secondly, the removal of impurities takes place immediately ahead of the paper machine proper, so reducing the possibility of later contamination.

The only exception to this is with certain speciality grades where the consistency of stock entering the breast box needs to be as low as 0·1 to 0·2 per cent. In this case the extremely high flows involved make screening and cleaning immediately ahead of the breast box an expensive business and little is gained in added purity by performing the operation at such a low consistency. Consequently an initial dilution from normal refining consistencies to the region of 0·5 to 1 per cent. is sometimes carried out for the purpose of screening and cleaning, while further dilution for making the sheet follows in a second mixing pump. The main disadvantage in this is that there is no protection against any impurities introduced in the second dilution, so scrupulous attention to cleanliness of machine pit, pipework and the second mixing pump becomes highly important.

135

Feed to the rotary or flat type of screen is frequently by open chute from a simple mixing box where fresh fibre is mixed with backwater either over adjustable weirs or by valves. The reject goes to a secondary screen where it may be diluted by sprays using machine pit water or lower-consistency water from the vacuum boxes or a save-all. The accepted stock from this secondary screen is normally returned to the main machine pit or to a suitable compartment of the mixing box, though it can be taken out of the machine system and returned to the stock preparation to help break down impurities by further beating and refining. With pressure screens a similar system is used except that the feed is from a mixing pump and pipework is used exclusively.

With this typical sort of arrangement it is always useful if a line to by-pass the screening equipment is available because frequently this will allow repair work to be carried out on the screen without stopping the machine. Whether or not this is feasible depends of course on how critical an operation the screening is: on some machines it is impossible to make a satisfactory sheet without screens even for a short time, but for coarser papers it is often possible to run for a while and suffer a temporary increase in shives in the paper. When a number of individual screening units are coupled in parallel the position is simpler and provision should always be made to allow a single unit to be isolated with the flow temporarily accommodated by the remaining units. In some cases an additional unit is installed and kept specifically as a standby; it should then rarely be necessary to shut the machine for repair work on the screens. For the same reason, provision for a temporary diversion round the secondary unit is also advisable.

Turning to cleaning equipment, with the more modern types a pumped system is always essential due to the relatively high feed pressures required. As with screens the reject is taken to a secondary unit or (in the case of cyclone cleaners) to a number of fibre-recovery stages. Some dilution is generally needed to ensure that the secondary and later stage units are kept full and to reduce the primary reject consistency which is normally somewhat higher than the inlet; this dilution can take place in level controlled open troughs or the system can be completely enclosed and pressures balanced by valves in the pipelines.

The accepted flow from the secondary unit or the second stage of a cyclone installation can be joined to the main accept flow from the primary cleaner, but normal practice is to return it for a second pass through the primary unit (as with screening equipment). Accordingly, the secondary accept flow is usually returned either to the main pit, or to the suction side of the pump feeding the cleaners. Alternatively it can go to the feed side of a specially designed box which contains two compartments, one for feeding the cleaners and the other for receiving the cleaned stock (the point of this arrangement is to permit some balancing recirculation over a weir between the compartments). Such boxes are carefully designed for ease of cleaning and due to the high pressures developed entry pipes should always be well below the normal operating level to reduce aeration. As with screening equipment, a by-pass round the primary cleaners,

isolation of secondary and later stages of fibre recovery, and isolation of individual units in parallel are valuable installation features.

2B.1 2 Using both screens and cleaners

Screens are very often the only type of equipment used ahead of a paper machine, especially for the manufacture of coarser grades where quite large contraries in the paper can be tolerated. Occasionally cleaners (usually of the cyclone type) are used without any screening equipment, but this practice is only found in integrated mills where pulp is well screened prior to entering the paper mill. However, it is becoming increasingly common to use both screens and cleaners, the former primarily to remove fibrous impurities and strings, the latter to remove heavier and smaller impurities. This poses one or two special problems.

Using screens and cleaners together makes no particular difference to the requirements and operation of each individual system, except that the doubling of protection makes it more feasible that one or other piece of equipment can be shut down temporarily for cleaning and repair, hence it is even more important to incorporate by-pass lines as discussed above. When a dump line is installed to divert the stock flow from entering the breast box, this should be immediately ahead of the breast box after both screening and cleaning equipment in order to allow the wire to be stopped or the breast box examined without stopping either screens or cleaners.

The main question confronting a papermaker when both screens and cleaners are required is: which order are they put in? At one time screening equipment was always placed immediately ahead of the breast box, mainly because it was felt that only in this position could full advantage be taken of the deflocculating action of screens. Also screens have a lower operating pressure, which can better suit entry into the breast box, and there is more opportunity for free air in the stock to be separated out and removed. On longer-fibred stocks these points still apply, though with improved approach flow systems and breast box designs such functions of a screen are probably less important than formerly. Nevertheless, it is undoubtedly still the case that screening equipment is considered most valuable when used to give the final removal of impurities of a more fibrous nature and reduce clumps, strings, and balls of good fibre immediately before the flow enters the breast box and is deposited on the wire. Thus, whenever flocculation or aeration are likely to be troublesome, there is a particularly strong case for screens immediately preceding the breast box.

However, with the advent of more efficient cleaners of the cyclone type this sequence of cleaners first, screens second has been questioned. Cyclone cleaners are prone to plugging of the quite small orifices used in individual cyclone units, at least when these are of smaller diameter, so to prevent this occurring it is considered preferable that screens are used first. By this means those larger particles are removed that can cause plugging or become trapped and create heavy wear of the cyclone body as they whirl perpetually round inside.

Installing screens before cleaners was a step taken somewhat hesitantly at first, particularly because it was feared that the stock would be too flocculated and full of air as it entered the breast box. One or two installations with both cleaners and screens were erected in such a way that either could be used first in the flow system. But there is now sufficient evidence available to show that at least with shorter-fibred stocks there is no reason why cleaners should not be used immediately ahead of the breast box. Perhaps the only precaution that may be advisable with certain arrangements of cyclone cleaners is to make provision for preventing suction of air into the accept flow.

Two examples of installations where cleaning equipment has been installed immediately ahead of the breast box are worth citing. Graham (16) described a system put in on a newsprint machine in which cyclone cleaners discharge straight to the breast box. These cyclones were equipped with eductors on the reject nozzles to reduce aeration of the stock entering the breast box, but otherwise no special precautions were taken. The formation showed no noticeable change after installation, and there were no obvious signs of increased flocculation of the stock.

A more recent example has been reported by Downey and Blake (31). In this case two Selectifiers (with reject to a Jonsson flat screen, from which accept goes to the wire pit and reject to the sewer) are followed by a battery of eight 12 in. cyclones of the Bauer type (reject under 16–18 in. Hg vacuum, accept from secondary stage to the wire pit and reject to sewer) before entry to the breast box. Improvement in cleanliness of the sheet was observed and no mention is made of any difficulties in operation. But it should be added that following this installation two other machines were re-built with the opposite sequence, i.e. screens following cleaners, though no reasons for the change in order are given (possibly the decision was governed by the use of a deculator in the system in place of a vacuum tank on the cyclone rejects, with the consequent need for two stock pumps instead of one).

2B.1 3 Effect on wet-end stability

In the normal position between the mixing pump and breast box, screens and cleaners have some influence on operation of the wet-end which is worth noting because occasionally trouble can occur with the stability of substance-keeping or dry-line position as a direct result of their malfunction. This comes about since any cleaning and screening equipment creates two kinds of changes in the composition and consistency of stock after it has left the mixing pump. Firstly, a certain amount of water and fibre leaves the equipment with impurities either as reject to drain or at any rate out of the immediate wet-end flow system. Secondly, dilution in some form is nearly always an essential feature of the operation so an addition of water and fibre, sometimes appreciable in relation to the stock flow, takes place.

Normally operation of the wet-end flow system is unaffected by this extraction and addition of water and fibre. This is not just because the

flows involved are small, though this is usually the case, but because whatever difference they make to breast box consistency and even to drainage conditions (as a result of a change in temperature or fibre characteristics of the stock) is automatically compensated for, once equilibrium of the backwater circuit has been reached, by appropriate setting at the mixing pump of the flow of fresh stuff and of the quantity of backwater used for dilution. To take an example, suppose a large quantity is needed either of spray water in a screen or dilution water in a cleaner, and this is at a very low consistency (perhaps extracted from the suction boxes). Then the consistency of stock leaving the screen or cleaner will be lower than entering it and this will in turn reduce consistency in the breast box. But the machineman will set the re-circulation of backwater to give him an appropriate dry-line position, so in fact he will automatically compensate for the addition of low-consistency water that occurs after the mixing pump. Less backwater will actually be circulated through the mixing pump, where consistency will be higher than is required at the breast box, the remaining dilution taking place in the screen or cleaner. In a similar way, fibre rejected from the system is in effect compensated for by a slight addition in fresh stuff.

A further point to note is that the fibre-length distribution at the mixing pump may also be different from that in the breast box due, for example, to the tendency for pressure screens selectively to reject longer fibres and cyclones to reject shorter fibres. But as with consistency the fibre-length distribution in the breast box will effectively stabilize at the same condition it would have reached without the screen or cleaner operating.

The presence of a fibre reject and of dilution at a screen or cleaner thus does not materially affect normal operation with regard to substance setting and such factors as drainage conditions on the wire. But what happens if either of these flows fluctuate for some reason? Consider the flow of rejected fibre from a screen or cleaner. When this leaves the closed backwater circuit (the flow from the main machine pit through the mixing pump to the breast box) then fibre contained in it is effectively deducted from the flow of fresh fibre to the machine system. Hence it has an effect on the value of paper substance. Should a large increase in this flow occur due to some disturbance, then the substance will be reduced. For this reason it is unwise to operate with a large reject flow from screens or cleaners when this leaves the immediate machine system, i.e. is taken (perhaps via a secondary screen or cleaner) either to waste or to the stock preparation or pulping system. There is no reason why a large reject flow should not be operated from a primary screen or cleaner provided it eventually returns to the backwater circuit.

As the usual course is to take the accepted flow from a secondary screen or cleaner straight to the machine pit, leaving only a very small final reject for disposal out of the system, in practice this should not normally be a source of any significant substance instability. But large variations in the primary reject flow, especially when rapid, can still affect the substance level temporarily in a similar manner to other variations in flow at the wet-end (as discussed in 1A.2). An example of this is seen if the reject

valves of pressure screens are opened too quickly for the purpose of purging: a marked series of bars can sometimes be seen passing down the wire and the head at the slice can drop momentarily, a disturbance that easily causes a break. In practice, apart from this, temporary disturbances due to variations in reject flow do not appear to affect operation.

Variation in the flow of spray or dilution water to screens and cleaners can likewise affect substance stability when the source of dilution comes from outside the immediate machine system. This applies even more to chemical condition of the stock and especially to pH. Dilution from sources other than machine backwater is frequently used for sprays, and also when backwater consistency is considered too high for adequate dilution, for example in cyclone cleaner fibre-recovery stages. The source can then be fresh water or, when large flows are involved, whitewater recovered in a fibre save-all is sometimes used. The effect on substance stability caused by a sudden change in addition of dilution water from outside the machine system will obviously not be so great as in the case of fibre reject discussed above, because its main effect will be on consistency levels while the effective fibre flows are relatively unaltered. An increase in the dilution flow would ultimately reduce breast box consistency, leading the machineman to compensate by reducing the quantity of backwater used for dilution at the mixing pump. At the new equilibrium the substance level should be unaltered except insofar as there has been any consequent change in the consistency of excess backwater leaving the machine system. On the other hand a fluctuating flow of dilution water would be undesirable because it could undoubtedly lead to transient changes in the substance.

2B.2 OPEN SCREENING EQUIPMENT

Attention is now turned to discussing the various types of screening and cleaning equipment used on stock in the paper mill. It is proposed first to deal specifically with screening and for convenience this has been somewhat arbitrarily divided into two sections. The present section covers open screening equipment comprising the diaphragm or flat screen and the various types of rotary vibrating screens; the next section will deal with the more modern enclosed pressure screens.

2B.2 1 Flat screens

The earliest type of screening equipment used in paper mills was probably introduced primarily to remove the large clumps and strings of fibre that appear in long-fibred stocks. Flat screens were the first to be installed and the vibration necessary to prevent the screen plates clogging was found to provide a useful deflocculating action on fibres. The flat screen as a primary screen is now obsolete, but it is still in general use as a secondary screen.

Over the years a multitude of different designs of flat screen have appeared on the market. The most common type has a box at one end

from which the stock flows on to a series of screen plates that may slope upwards; accepted fibre passes through the plates to a vat underneath while rejected material discharges over the end of the plates. Sprays and scrapers are used to aid the process and help break down clumps of fibres that clog the perforations or become stapled across two adjoining slots. Flat screens differ mainly in regard to how the pulsation is applied: this is either to the vat underneath by means of a cam and springs or by a positive rocker mechanism, or to the plate itself by means of a motor driving through an eccentric. The first type, which is the older, requires a dam underneath in the vat to ensure that the accepted stock level is high enough for the vibration to be transmitted to fibre on top of the plates; the second type allows a much higher frequency of vibration and is generally shorter in length. Other models of flat screen have appeared, some with the flow upward from a vibrating vat through a curved screen plate which then contained the accepted fibre until it was sucked out by means of a simple water ejector system. However, none have found such general acceptance as the main two types described.

Flat screens are not easy to operate or control efficiently. It is usually possible to change the amplitude or frequency of the vibration, but this rarely seems to make any obvious difference to performance. Usually careful positioning of sprays on top is a more satisfactory means of adjustment. Screen plates of the vat-vibrated type are commonly in $\frac{3}{8}$ in. thick bronze, chromium plate or stainless steel, and there are normally several that can be removed individually. They are usually cut with 3 in. to 4 in. long slots, which are 6 to 60 thou wide (normally 8–12 thou) and have a downward taper, though relatively large diameter ($\frac{1}{8}$ in. to $\frac{3}{16}$ in.) holes are also used. The slots are arranged from 4 to 8 to an inch in a variety of patterns which are thought by the designers to promote efficiency. The other type of flat screen usually has a single plate and the life of this can be quite short due to the high frequency of vibration it is subjected to. Regular cleaning is essential for all flat screens otherwise it will be found that the flow of fibre over the end of the plate has increased to uneconomic proportions; ease of access to the vat for cleaning underneath, and with the upward-flowing type ease of turning over the plate to allow the impurities to be removed from the vat and the underside of the plate cleaned, are as important features as any to look for in flat screens.

Examination of the material passing over the end of a typical flat screen gives a convincing indication of efficiency. When working properly, there is always a very high proportion of large impurities embedded in a relatively small amount of fibre. The impurities separated out obviously depend on the stock, but shives, knots, unbroken pieces of broke and Cellophane, etc., and tight strings of fibres are commonly seen mixed with any really large objects (pieces of wood, rubber bands, and so forth) that have found their way into the system. The only systematic examination of the performance of a flat screen is due to Lambert (34) who examined one of the high-frequency vibration type with $\frac{1}{8}$ in. holes which received the reject from a number of primary screens working on newsprint stock. Samples of the feed, accept and reject flows were taken and measured

for consistency, C.S.F., and fibre fractionation. It appeared from this work that a relatively efficient separation occurred in the sense that the freeness of the reject was very high compared to the inlet (496 compared to 61) and there were five times as many fibres retained on a 14-mesh screen. But when the low reject flow rate was taken into account the true efficiency of separation (using the greater than 14-mesh fraction as a criterion of 'objectionable material') was in fact so low (0·3 per cent.) as to be negligible. Confirmation of the low efficiency of flat screens can also be found in a report by Downey and Blake (31) in which they calculated that 90 per cent. of shive passing from the reject of a closed screen was accepted by a secondary flat screen.

Lambert considers that reducing the hole size would not improve this situation as it would only produce a greater reject flow and lower capacity, while not affecting the true efficiency. He concluded from his examination that, at least for secondary screening of newsprint, it was difficult to justify using a flat screen. One can question the definition of efficiency used by Lambert, but it does seem that in practice a certain quantity of larger shives and other large contraries will be removed, but the majority will pass straight to the accept flow and thence back into the stock system. Inevitably such material will eventually find its way into the paper so the only merit in using a secondary screen seems to be to provide some means of achieving relatively little fibre loss.

2B.2 2 Rotary screens

As with flat screens, there have been numerous types of open rotary screens marketed. The original models were outward flowing, i.e. stock entered through a hollow journal into the inside of a rotating cylindrical screen and passed out into the vat. But nowadays these are mostly used on fine papers with a high content of long fibres and most models in use are of the inward flowing type. In this case stock enters the vat over rubber sealing strips or from the bottom, passes inside the cylinder, and is discharged through one end which is sealed from the bearing. The preference for the inward-flowing rotary screen is partly because it is easier to clean and arrange a continuous reject flow, and partly a question of mechanical design and reduction of maintenance which, with vibration an essential feature, can become heavy.

Showers are always a vital part of the operation of any rotary screen and these must be positioned to ensure that fibre is washed away from the surface on the ingoing side and no part of the plate is missed because of poor overlapping of individual jets (oscillating showers give the best protection against this). With the outward-flowing type of screen a direct spray on the outside of the plate pushes fibre sticking in the slots into a trough inside the screen; with the inward-flowing model the sprays are either internal, or glance the outside of the plate at a fine angle on the upgoing side to avoid forcing fibre through as it is washed back down to the vat. The cylindrical screen plates are in sections and invariably cut with slots which can be anything from 8 to 35 or more thou wide (normally 18–20 thou) and which taper out in the direction of flow; they are made

of stainless steel, phosphor bronze, or monel, and are often chrome-plated, or plastic-coated.

Various methods of imposing a vibration on the screen are used. With the outward-flowing models, in some types the cylinder itself is shaken from pivoted bearing arms or by means of a rotary-eccentric centre bearing at one end, and in another type the vat itself is vibrated by being supported on straps one end of which are fixed and the other attached to a jogging lever. In yet another arrangement rotation of the cylinder instead of being smooth is in jerks by a ratchet device. With the inward-flowing models, either the whole vat is supported on flexible mounts and vibrated sideways from an eccentric shaft, or a semi-cylindrical plate or perforated diaphragm underneath the main rotating cylinder is vibrated up and down or from side to side.

Rejects from the outward-flowing rotary screens comprise light material skimmed off the stock surface in the cylinder together with fibre and impurities washed into the trough by sprays. From inward-flowing screens either larger impurities settling in the bottom of the vat must be cleaned out when the screen is stopped or more usually there is a continuous bleed-off from the lowest point at the bottom of the vat; lighter material may be skimmed off the top in an overflow. The reject flow can be altered within a wide range and is usually governed entirely by the capacity of secondary screening equipment.

Although open rotary screens are rapidly becoming obsolete there has been one interesting development of a new screen of this type designed for a specific purpose. Robinson and Kingsnorth (29) tackled the problem of removing long flexible hairs (sisal) from a chemical/groundwood stock by building a rotary screen which is basically of the outward-flowing type with sprays backwashing the screen plates into a trough inside the cylinder having a discharge at one end. The main feature of this screen is the use of a coarse wire mesh (six meshes to the inch) as this was found by experiment to present the best efficiency: dyed sisal hairs between about $\frac{1}{4}$ in. to 1 in. length were rejected at over 90 per cent. efficiency, though this level of efficiency had to be sacrified during modification of the design to attain greater throughput with an acceptable fibre loss in a full-scale version. The authors state that using an open-mesh screen instead of the usual slotted type of plate for this particular purpose has the advantage of giving a much greater throughput. The screen acts as a tangling device for the long hairs while presenting a minimum of restriction to the flow of fibres. This development represents a good example of the best way to approach the removal of impurities from stock systems, by considering the individual sources of impurity that must be taken out and then deciding the most economical manner of achieving this end. Not everyone of course will be prepared to go to the expense of developing a new screen, nor is this likely to be at all necessary, but the point is worth making that only sufficient screening or cleaning capacity should be provided to do the job required for the particular grade of paper concerned, otherwise it will invariably be the case that more power will be needed, or more fibre lost, than is strictly necessary.

Lambert (34), in the work already referred to above, also checked the performance of a bank of five rotary screens of the inward-flowing type with a 25 thou slot. The C.S.F. of the reject flow was no different from that of the inlet, though the consistency was slightly higher. The true efficiency of separation, measured on the same basis as mentioned above for the flat screen, was higher but still only 2·8 per cent. for material retained on a 14-mesh screen. Lambert comments that this shows the screens gave virtually no separation.

If this result can be generalized (and there is no reason to expect other screens to act more efficiently, at least with regard to the basis of measurement used in this work) it would seem that open rotary screens can serve little screening function except for the removal of really large impurities. Of course in many cases the deflocculating effect of open screens can be an invaluable asset, and for some stocks the prevention of large strings of fibre passing to the breast box is highly important. But when it comes to removing smaller shive-like material, the efficiency appears so low as to make the expense totally uneconomical.

2B.3 CLOSED PRESSURE SCREENS

Since the introduction of the totally-enclosed pressure screen, this type has come to predominate on modern paper machines and in the vast majority of cases is installed both on new machines and when re-building the wet-end of old machines. Certainly for the larger machine making relatively coarse grades, the pressure screen is far superior in design to the open rotary screen, for reasons which will emerge in what follows. Only on slower fine machines, especially with a long-fibred furnish, may an open screen still often be preferable, mainly because any tendency for clogging of the screen plates to occur can be immediately seen and quickly remedied.

2B.3 1 General details

In the closed pressure screen, stock enters at the top tangential to the wall of the screen. It then passes downwards either into an annular region between two cylindrical screen plates or into the centre of a single cylindrical screen plate. Passage outward through the plate, and inwards also when there are two plates, is assisted by means of impellers rotating on a central shaft supported from below. There are usually two devices collecting rejected material; one collects larger objects thrown out in the initial entry to the screen and is emptied intermittently, the other represents a bleed-off from the bottom of the screen consisting of fibre and material that does not pass through the plates (this is almost always a continuous flow). Accepted flow leaves centrally from the screen at a point level in height with the plates. One model is an exception to this and here the flow passes inward through a single screen plate and then leaves tangentially. Capacity of a single unit is from around 1,000 gallons per minute upwards.

One of the most critical features in the operation of enclosed screens is the impeller arrangement. The head is of an aerofoil design and is set so that the leading edge skims close to the screen plate with the gap between the impeller head and the plate widening gradually towards the trailing edge. Setting the gap between the impeller head and screen plate (normally between $\frac{1}{8}$ in. and $\frac{1}{4}$ in.) and the angle formed between the head and plate on the trailing side are both quite critical. The shape of the impeller head is designed so that stock trying to pass through the plate receives an initial shock assisting it in that direction, followed by a substantial suction (akin to that formed by a foil under a Fourdrinier wire) that clears any fibre or dirt left lodging in the holes. This effectively reduces any tendency for the screen to make up, though especially with longer-fibred stock clogging still represents a hazard on many installations. When clogging begins to take place, power required to drive the impeller increases and above all the pressure drop across the screen rises appreciably; eventually the screen seizes up altogether and it can then be a lengthy operation to clean it, necessitating removal of the top cover (this is easiest when hinged on a davit arm) and also the screen plates as well.

Adjustment of the clearances between impeller heads and plates can sometimes reduce any tendency to clog, but on the other hand it can also affect power consumption and in adverse circumstances promote hydraulic pulsations (due mainly to flexing of the screen plate) which can show up as a short cycle machine-direction substance variation down the wire. Altering speed of rotation of the impellers also affects the running condition of a screen, lower speed tending to reduce power demand and any hydraulic pulsations but (due to poorer clearing of the plates) at the expense of a higher pressure loss across the screen. Occasionally four-bladed impellers are used instead of two-bladed and this too appears to reduce hydraulic pulsations and is claimed to give a stronger screening action, however power consumption rises as does the fibre discharged in the reject for a given valve setting. When several enclosed screens are in parallel, it is occasionally necessary to arrange the motors to be deliberately out of phase otherwise there are periods lasting a few seconds when an intense mechanical vibration is set up which has the same effect on the substance as hydraulic pulsations from the impellers but is usually far more violent.

The large material thrown out on entering the screen accumulates either in a collecting chamber in the form of a box or a straightforward section of pipe. In both cases there are usually two valves, an upper and a lower, the former of which is left open to allow the debris to settle under gravity into the collecting chamber. Periodically, depending on how rapidly the collecting chamber becomes filled, the upper valve is closed off and the box emptied by opening the lower one. Before the upper valve is again opened it is useful to be able to flush out and fill the chamber with fresh water to prevent a sudden suction of air into the stock system. The whole business of periodic cleaning out of the collection chamber can be made automatic if the expense seems justified; in one arrangement, at a pre-set frequency a special rotary three-way valve connected to a timing device changes for a short time from the normal position (connecting the

screen to the collection chamber) to a second position (connecting the chamber to drain). Examination of the debris found when this part of the screen is emptied often shows surprising objects.

The continuous reject is always at a much higher consistency than the inlet flow. It is led to a secondary screen, usually of the flat type as when using open rotary screens, and the flow is generally controlled to suit the capacity of the secondary screen, being in the region of 3 per cent. to 8 per cent. or so of the inlet flow. Especially when the flow has to be kept fairly low due perhaps to lack of capacity in the secondary screen, there is a tendency for a blockage to occur in the valve controlling the flow. This is not always easy to detect, particularly when there are a number of screens in parallel and their reject lines join into a common manifold. To avoid the possibility of this going undetected, a separate and visible discharge is preferable and a purge line into the upstream side of the valve can be useful. Alternatively one of a number of different designs of special purging valve incorporating an automatic timing device can be used. These valves are arranged to open a specified amount and close back to their original position at regular intervals, and this effectively clears any fibre built up in the throat of the valve. The only precaution needed in their use is to avoid too large and rapid opening of the reject valve as this can temporarily starve a screen to an extent that affects the substance of the sheet and can cause a break (see the discussion in **2B.1 3**.)

There are also facilities for removing a small bleed-off from the top cover of a pressure screen. This is generally necessary to prevent air building up under the cover and eventually gulping away into the accept flow; also, if much air is allowed to collect the screen impellers begin to create excessive turbulence and this magnifies hydraulic pulsations and creates a rise in the power consumed. Although the air vent is sometimes opened only at start-up and then closed, it is generally preferable for a small flow to be removed continuously and taken to the secondary screen.

2B.3 2 Comparison with open rotary screens

For practically all screening operations the enclosed pressure screen has now replaced the open rotary screen. There are many reasons for this. The initial capital cost and the power consumption when running are both lower relative to screening capacity. The enclosed screen requires less space and is better adapted to the higher stock pressures involved on fast machines where a considerable head is needed at the slice and the breast box is pressurized. Also, being enclosed and operated with an air bleed-off reduces the possibility of trouble from foam and slime, and continues the general trend from open surfaces (chutes, mixing box, etc.) to closed systems (pipes, mixing pump, etc.) which has characterized development in recent years. Enclosed screens also generally require lower maintenance than the open rotary type because their impeller rotation is smooth and it is not necessary to induce a vibration into the equipment; also there are no showers which can often be a problem to keep working satisfactorily. Finally, the reject flow from an enclosed screen is much more readily controlled.

146

This is a formidable list of advantages, so it is hardly surprising that there has been a complete swing over to using enclosed screens. Practically the only disadvantage of the enclosed screen is the relatively high consistency of the reject (which as mentioned above can be troublesome to ensure a steady flow) and the time needed to clean down if clogging of the screen plate occurs.

So much for a comparison of operating features, but what about relative performance? The consensus of opinion here is that enclosed screens
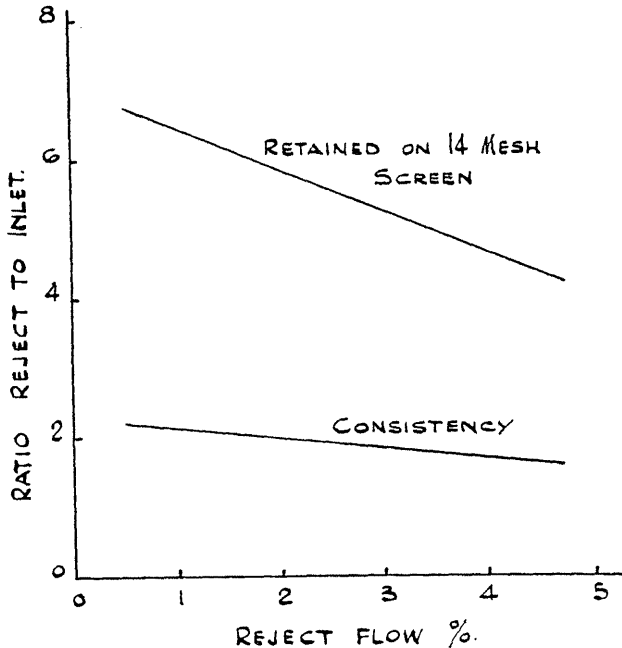
Fig. 2.11. Effect of altering the reject flow from an enclosed screen on the reject/inlet ratio for consistency and for the fraction retained on a 14-mesh screen (after Salomon and Lukianovitch)

prove more efficient than open rotary screens in some respects but not in others. Before discussing this in detail it will be as well to set down what data is available on the performance of enclosed screens.

2B.3 3 Performance of enclosed screens

Thickening of the reject flow in comparison with the inlet can be appreciable. Salomon and Lukianovitch (23) reported that the reject consistency of an enclosed screen was nearly double that of the inlet with only a slight drop in the ratio as the reject (or 'tailings') flow was increased, see Fig. 2.11 (lower curve). They also found that there was a larger proportion of

longer fibres in the reject flow with a consequent increase in the percentage of fines in the accept flow. Other reports (for example, reference 17) have confirmed these observations and also indicate that the thickening ratio increases at lower inlet consistencies. On a newsprint grade the proportion of sulphite fibres in the inlet stock can be doubled in the reject, though the proportion of loading particles remains unaltered.

Lambert (34), in the investigation already referred to in **2B**.2 1 and **2B**.2 2 with reference to open screening equipment, also checked the performance of an enclosed screen on newsprint stock. He found that efficiency of rejection for material kept back on a 14-mesh screen was 40 per cent. This may be compared with 0·3 per cent. for a typical flat screen and 2·8 per cent. for a rotary screen. With a greater reject flow the percentage of larger material rejected was even higher, though this could of course lead to greater fibre loss from the system. Both the main types of pressure screen, the Centriscreen and Selectifier, gave a similar performance in this respect.

A similar result was found by Salomon and Lukianovitch, and is also shown in Fig. **2**.11 (upper curve). They reported that the concentration of material greater in size than a 14-mesh screen was six times as high in the reject as the inlet with a 1 per cent. reject flow, dropping to a little over four times for reject flow 5 per cent. of the inlet, the usual running condition. The first of these results represents, in the terms used by Lambert, an efficiency of about 12 per cent., but the second is over 40 per cent. which confirms his own figure. Macmillan (35) reported a reduction in shive content from 2·75 per cent. to 2 per cent. on a newsprint stock, representing a rather lower efficiency of 27 per cent.

The implications of this data are that as a means of removing shive-like material the enclosed screen is relatively efficient. Indeed inspection of handsheets made from the reject flow from a screen operating on stock containing groundwood furnish gives a ready indication of this. Operating experience when enclosed screens have been substituted for old rotary screens also amply confirms this. But there have been many reports that such a change in equipment is also accompanied by an increase in the appearance of relatively large particles of a more spherical shape.

Thus, Salomon and Lukianovitch recorded that when a pressure screen was first used there were many holes in the sheet, especially after each start up, due to particles of sand and pipe scale. Sloping the impeller hydrofoils to give a downward motion and running with high reject flow assisted in overcoming this difficulty, but many other mills have met the same problem and not been so fortunate in finding a permanent solution. Another report, by Hopkins *et al.* (32), compared the performance of a number of machines using essentially the same furnish. Those with pressure screens were excellent for removing long and thin slivers and unbroken pieces of broke, but overall cleanliness of the sheet was lower.

2B.3 4 Slots versus holes

The reason for poorer rejection in enclosed screens of heavier and more spherical-shaped particles is thought to be due principally to the use of

circular holes in pressure screens as opposed to slots in rotary screens. Although slotted screens are available for at least one of the enclosed models, not a great deal is known about their performance. Theoretical considerations already outlined in 2A.1 3 show that the use of holes in a screen plate instead of slots of a similar area would favour acceptance of solid spherical particles and rejection of shive-like material. This would seem to be precisely what happens when a pressure screen with holes replaces a rotary one with slots. The fact that the open area corresponds, a 62 thou hole to a 16 thou slot, a 79 thou hole to a 20 thou slot and so on, does not affect the situation.

It is sometimes argued that although an enclosed screen has holes, because of the fast rotation the view presented to the stock is of an elongated hole or slot. In other words it is in effect no different to an open rotary screen. This is patently fallacious because at the point which stock passes through holes in the plate its velocity must be substantially parallel with the direction of the hole. In the boundary layer from where stock passing through the holes is drawn, the chances of acceptance or rejection will be governed primarily by the interaction of the various factors, including particle shape and hole shape, which were discussed in 2A.1.

Efficiency of rejection of smaller solid particles can be improved by reducing the size of the holes. Normally holes are from 60 to over 100 thou diameter for coarser screening, but in some cases a diameter of 45 thou can be used. Unfortunately the smaller the hole size, the higher is the power demand and pressure drop across the screen and the greater is the tendency for clogging to occur. In practice the hole size is chosen at a level governed mainly by the necessity of avoiding clogging.

It is clear that particles up to 60 thou in diameter can pass through the typical pressure screen, whereas with an old open rotary screen having 20 thou slots, no solid round particles of a diameter less than that can pass. If the greater size of particles accepted by the enclosed screen is unsatisfactory, there is no alternative but to use the rotary screen and with it the very low efficiency of shive removal.

With the growing demand for improved cleanliness of paper, and particularly since work has been reported showing beyond doubt that shives are a major source of breaks in the high-speed printing of newsprint, it has become more essential to ensure a high efficiency of shive removal. This means using pressure screens, and if this gives an unacceptable level of particle impurity in the sheet (or at worst leads to trouble with holes in the web) then cleaners become an essential adjunct. Fortunately centrifugal cleaning equipment, especially of the cyclone type, though often very inefficient at rejecting shives particularly the larger ones that cause the trouble, is highly efficient with solid spherical particles. Thus the two pieces of equipment complement one another especially on groundwood furnish: cleaners to remove solid particles, grit, stubby debris, etc., which spoil the sheet appearance and wear wires, suction box surfaces, and calender rolls; screens to remove long, thin shives and unbleached lumps which, though not so numerous relatively, probably cause breaks more often.

2B.4 EARLY CLEANING EQUIPMENT

Early forms of cleaning equipment were of two types: the riffler or sand table which relies entirely on natural settlement to separate out heavier particles; and the enclosed rotating basket type of cleaner which represents the first attempt to utilize the powerful separating potential of centrifugal force. Each of these cleaners is now briefly dealt with.

2B.4 1 Sand tables

Rifflers or sand tables are a straightforward application of an age-old method of purification by settling. Stock is allowed to flow gently down a slight slope which is usually interposed at intervals by baffles meant to catch the heavier particles settling out. The whole flow has to be very shallow and slow to permit a reasonable settling time, though not so slow as to allow fibre and loading to settle also. This means having a very large area available and is one of the main disadvantages of the sand table, apart from exposing a large area of stock to further contamination from air impurities. Baffles are 4 in. to 8 in. high and the whole floor is sometimes covered in long-nap felt intended to help catch and hold the dirt. Sometimes an electromagnet is placed across the trap to attract metallic particles. Also boards are hung with their edges just below the top surface to skim off floating scum, rubber, and so on. Regular cleaning out is absolutely essential as once a fair layer of dirt is built up behind a baffle it is very easily disturbed. Usually the table is arranged in parallel banks each of which can be dammed off in turn for cleaning out.

The sand table is reasonably efficient at removing the larger and more obvious contaminants that appear in paper stock from time to time, but it is often difficult to get the flow right for removal of grit and sand. There has always been some difference of opinion about just how deep the flow should be and how the baffles should be set to produce a mild amount of turbulence, sufficient to keep the fibres in suspension but not disturb dirt collecting against the baffles. With wet-beaten stock at a fairly high consistency the flow readily becomes sluggish and begins to divide into channels of relatively fast-moving low-consistency stock separated by dead areas from which fibre settles out and which become thicker as time passes.

The sand table has been obsolete since pre-war days, yet curiously enough the first real study of its performance did not appear until the classic report of Chester (1) in 1950. In addition to a theoretical considera- tion of the flow in a sand table, Chester carried out comparative experi- ments on a laboratory model using ground coal particles in an unbeaten bleached sulphite stock, assessing cleanliness by counting on standard handsheets. The effect of variations in depth of the baffles, flow rate, consistency, different shapes of baffle, temperature, beating, particle size, and several other variables were all investigated. The best results appeared with a table lined with old machine wet felt, and stock flowing at about 6·5 inches per second to a depth of one inch. This gave a mild degree of

turbulence just sufficient to prevent settling of fibres. Higher temperature increased efficiency but beating caused a decrease.

The coal particles were observed to settle out in a fibre-free layer adjacent to the bottom of the table. If flow was so slow as to be streamline conditions for settling were inhibited by the fibre because this tended to settle at the same time. Thus, some degree of turbulence must be induced to promote settling and Chester examined the value of various methods in common use. Baffles dipping into the surface caused a slight improvement, as did vertical baffles under the surface. The traditional undulating riffle was better than simple baffles, but ordinary felt appeared to be the most efficient. Even with this there was hardly any reduction in the number of small particles and overall efficiency was extremely low.

2B.4 2 Rotating basket cleaners

The principle of the rotating basket cleaners, the first type to utilize centrifugal force, depends on the rotation of an elaborate arrangement of cylindrical containers and baffles. Stock introduced down a funnel at the centre of the device accelerates in a tangential direction under the influence of the revolving compartments and then has to pass under and over a series of strategically-placed baffles designed to promote retention of heavier particles flung against the walls of the compartments. In some models light impurities are retained on specially-placed rings and in others it is customary to have one large central distributor surrounded radially by a number of individual cleaning units.

The whole operation of this type of cleaner depends on the building up of thick layers of pulp in the various positions where impurities collect. This is essential to ensure retention of impurities against the wall of the compartment and reduce turbulence in that region, so aiding the capture of further impurities. But inevitably there is a tendency for more and more pulp to build up into a solid lump until a large part of the device is rotating as a relatively stable mass and further stock introduced tends to pass straight through. It is then necessary to clean the whole contraption, at which point the elaborate design of compartments and baffles becomes a positive nuisance. Hosing out is often not practicable except for finishing off because the pulp is so thickly embedded against the walls of the compartments that it all has to be dug out by hand. When starting up, consistency of the accepted stock is at first low until a substantial layer of fresh pulp has been built up, so when a change of unit is made while the machine is running the substance can be badly affected.

These devices were probably about the most clumsy, useless, and wasteful ever to find their way into paper mills. Despite their high cost, capacity is very low and there always has to be one spare because it is not possible to run for long before the tedious business of cleaning out becomes necessary. The cumbersome arrangement of compartments and the whole size of the contraption limits the rotational speed that can be built up, and so minimizes the benefit of centrifugal force. Maintenance is usually heavy, fibre loss considerable, use of floor space excessive, and running

costs high. On a machine with frequent colour changes revolving basket cleaners can account for a really excessive fibre loss and much wasted time in cleaning. Perhaps the most charitable statement that can be made is that they were probably more efficient than sand tables, but it is hardly surprising that as a cleaning device their appearance in paper mills was rapidly superseded by cleaners that utilized centrifugal force in a much more simple and efficient fashion.

2B.5 CYLINDRICAL CLEANERS

There is no difference in principle between the operation of cylindrical and cyclone cleaners, both rely entirely on the separating effect created by high centrifugal force. In practice the main difference between the two types is that the cyclone cleaner, by virtue of its shape, can discharge the reject flow into free air (though as will be seen there is a growing tendency for this facility not to be used) while the cylindrical cleaner has a special device at the bottom of the cylinder designed either to channel the reject off to a secondary cleaner or to effect a separation of rejected material into a collecting bottle. The cylindrical cleaners are generally larger than cyclones, so fewer units are needed to cope with a particular stock flow; however, there are now both large-diameter cyclone cleaners and relatively small-diameter cylindrical cleaners available, so this distinction too is blurred. Information given below is drawn from a number of references, in particular numbers 2, 11, 12 and 14.

2B.5 1 General details

The cylindrical cleaner has a tangential inlet at the top of the cylinder (this can be specially scrolled to assist the flow) into which stock is pumped at a pressure of between 20 and 40 p.s.i. The tangential motion continues down the cylinder until one or more baffles are met which turn the main body of the flow inwards and upwards. This inner column emerges as accept flow centrally from the top of the cylinder into a pipe, or in some models it is arranged to emerge tangentially thus continuing the generally circular motion imparted at the inlet. The baffles in the lower part of the cylinder are of various arrangements designed to encourage the flow from the outer wall of the cylinder to continue downwards, taking with it such impurities as have been thrown outwards. Beneath the baffles the cylinder tapers to a pipe section with a valve below which is a chamber for collecting rejected material; additionally there can be a continuous reject taken out centrally or tangentially from the side of the cylinder and in some models elutriation water can be injected into the cylinder for the purpose of reducing the consistency of this reject.

Cylindrical cleaners vary from as low as $1\frac{1}{2}$ in. diameter (capacity around 20 gallons per minute) to 10 in. or over with a capacity of 1,000 gallons per minute and higher. The capacity increases with higher pressure drop across the cleaner, either when inlet pressure is raised or accept

pressure reduced to a minimum of 1 to 2 p.s.i.; the pressure drop is normally 20 (in larger units) up to 40 p.s.i., above which the increase in separating efficiency is not considered worth the added pumping costs (for a fuller discussion of this point see section 2B.6 5 on cyclones). Material of construction is stainless steel, bronze or cast iron with wear-resistant lining; parts exposed to wear are often chrome-plated or in ceramic. In some models designed to de-aerate stock a low inlet pressure of 10 p s.i. or so may be used, vacuum is applied to the reject (which discharges continuously to a secondary cleaner), and the accept flow is usually taken direct to the suction of a pump feeding the breast box.

When there is a continuous reject flow it is usually diluted with backwater to a lower consistency before being pumped into a secondary cleaner. This is generally similar in design to the primary unit though often smaller in diameter and with a consequent lower capacity. Occasionally a tertiary stage can be used, though with cylindrical cleaners this is rare. Often, however, there is no continuous reject and material settling at the bottom of the cleaner is simply allowed to accumulate in a collecting chamber which is equipped with a window for easy observation. Even with a continuous reject this same arrangement is also used, as it is on the secondary cleaners. The collecting chamber slowly fills with impurities and fibre, and must be occasionally emptied. The procedure for this is to close the upper of a pair of isolating valves and dump the contents of the chamber by opening a valve or plate at the bottom; rather than start with air in the chamber, it is then preferable to fill up with water using a fresh water line and air vent. This whole procedure can be made automatic if this is thought necessary. Fibre loss is kept small by this means, generally from 0·02 per cent. to 0·2 per cent. depending on the use or otherwise of secondary cleaners and whether or not loading is present in the stock. In one unique design rejected material settles into a chamber below which is a screw arrangement which compacts and pushes out against a counterweight like a giant mincer. In another an automatic reject valve gives a constant volume discharge from a vane rotor. There are also several other special adaptations designed to allow some measure of control and provide a continuous reject flow.

Because of the high velocities generated, cylindrical cleaners are vulnerable to damage if large hard objects are allowed to enter the body. For this reason some form of pre-treatment is advisable to remove really large impurities, nuts, beater tiles, bale wire, etc. Alternatively it is possible to use the cleaners after screening equipment and immediately prior to entering the breast box. Points regarding this have already been discussed in 2B.1 2.

Some manufacturers advocate the use of cylindrical cleaners to handle the rejects of a primary screen either of the open rotary or enclosed type. This practice has nothing to recommend it because it has been seen that there is ample evidence to indicate that impurities removed by cleaners are of a completely different type to those removed by a screen. Large shives efficiently separated out in the screen will simply pass straight through a cleaner treating the rejects; the cleaner can in fact be expected to remove

only the heavy large dirt that is screened out by virtue of its size, together with such small, heavy dirt as happens to pass out with it.

2B.5 2 Running conditions

Despite the popularity of the cylindrical cleaner there have been extremely few details published of experimental work on its operation. This is in sharp contrast to the cyclone cleaner for which there is a wealth of data available. Many operational reports have been made but hardly any can be considered of useful general validity.

It is generally stated that efficiency of separation of heavy material is improved by increasing the pressure drop, i.e. difference between inlet and accept pressure, and by reducing consistency. So far as they go these are reasonable points to make in the light of the mode of working of the cylindrical cleaner, but reference to the effect of pressure and consistency in cyclone cleaners which are likely to be basically similar in performance will show that other factors need to be considered. In particular some economic qualification is necessary to take regard of the increased pumping cost needed when pressure is increased and consistency reduced, and also the greater proportional fibre loss likely to occur at very low consistency.

One report on a cylindrical cleaner (15) commented on the effect of furnish and consistency. With a long-fibred stock, efficiency of rejection of sand dropped from 90 per cent. at 1 per cent. consistency to 74 per cent. at 0·5 per cent. consistency. On a newsprint stock, however, reducing consistency appeared to make no alteration in the efficiency of sand removal which remained at over 90 per cent. This was for unchanged inlet pressure. Another report (8) gave some comparisons of the efficiency of various models produced by the same manufacturer but nothing of general validity can be deduced from this.

Unfortunately there appears to be no test results reported in which cylindrical and cyclone cleaners can be compared on the same basis, an unfortunate hiatus in available knowledge since this would provide most interesting data. There have been reports of improvement brought about when cyclones have replaced old cylindrical cleaners, but as the latter would most likely have been of larger diameter than the cyclones replacing them, and probably would have been of the early type with no secondary cleaner or only a simple collecting chamber, it is hardly surprising that the performance of cyclone cleaners appeared better. Whether a comparison of similar diameter cyclone and cylindrical cleaners, both having a continuous reject system, would yield similar results for both is completely unknown.

2B.6 CYCLONE CLEANERS

Since its introduction in the early 1950s, the cyclone cleaner (otherwise called 'Centricleaner', 'Hydraulic cyclone', or 'Hydrocyclone') has grown rapidly in popularity until today it is undoubtedly the most common stock cleaner in use. This is despite the disadvantage, inherent in earlier

installations, of excessive maintenance and a certain clumsiness of arrangement. Since its inception a considerable amount of experimental work has been reported and a great deal is now known of the behaviour and peculiarities of cyclone cleaners when used on paper stock. This section is therefore devoted to a fairly thorough examination of the data available, and is drawn mainly from references 3, 6, 7, 8, 9, 10, 13, 16, 19, 22, 25, 26, 27, 28, 30 and 33.

2B.6 1 General details

The basic design of the cyclone cleaner and some general details with regard to feed arrangements and positioning in the stock line have already been described. Cyclones on the market, of whatever diameter, all follow this basic design with minor differences in the relative diameter of inlet and accept orifices, angle of cone, shape of the inlet (whether directly tangential or spiral), depth of the vortex finder, and so forth. Little evidence is available to show the superiority of one particular geometrical arrangement over another though it is claimed that under comparable conditions a higher cone angle gives a lower removal of fibre though capacity and efficiency of removal of impurities is also lower. Apart from this, about the only important distinctions which arise in practice relate to devices attached to the reject orifice. These are dealt with later.

Cyclones are built from or lined inside with a variety of materials including rubber, stainless steel, porcelain or ceramic, nylon, and other vinyl plastics, with particular attention being taken to make the bottom of the cone as wear-resistant as possible because it is in this region that rapid abrasion occurs, manifesting itself in particular as an uneven widening of the reject orifice diameter. Normal input to a cyclone battery is from a pipe manifold (preferably tapering towards the end) with a pressure in the region of 30 to 50 p.s.i.; the cyclones are usually suspended in a double row on either side of the inlet manifold and tilted slightly from vertical so that the reject tips are closer together. Pressure in the accept is kept as low as possible, just sufficient to allow unimpeded exit from the individual cyclones into a common manifold and thence either to a chest or pump, or direct into the machine breast box. Isolating valves or cocks on the inlet and accept pipes of each cyclone are advantageous to permit easy maintenance. An alternative arrangement designed to remove air from the stock as well as clean it involves the accept flow discharging direct on to plates in an evacuated chamber and the rejects joined into a common pipe which is also under vacuum; in this case inlet pressure need not be so high since it is the overall pressure drop from inlet to accept which governs the general efficiency of working. Rejects from open cyclones discharge as a spray of stock into a trough which is level-controlled by addition of backwater and serves as feed for the second stage. Similar arrangements serve succeeding stages. The common sizes of cyclone are 3 in., 6 in., and 12 in. though other diameters are available. Throughput varies from 10 to 20 gallons per minute for the smaller units up to as high as 1,000 gallons per minute and even higher for cyclones used in coarse cleaning.

A relative newcomer to the category of cyclone cleaners is the Radiclone which departs in several respects from the conventional design. In this device 25 2-in. diameter cyclones are arranged radially in a horizontal circle with apex pointing inwards, and a number of such circles are stacked one on top of the other and enclosed in a large cylindrical container. The whole container is divided up into annular compartments so that a single pipe at the bottom serves as a common feed to all the cyclone units, while there are similar compartments for the accept and reject flows and (when used) the elutriation water. To allow the cyclone units to be examined the cylindrical container is raised by a hydraulic jack and the units can then be individually extracted with a special tool. Sealing of the whole cylinder is by inflated rubber hoses; fins on the individual cyclones ensure sealing between compartments.

Apart from the improvement in appearance over the conventional cyclone lay-out, the Radiclone would appear to be advantageous in requiring less room for a similar capacity, being totally enclosed, and operating at a lower input pressure than usual (under 30 p.s.i.) which means a saving in power costs. But the most important aspect of this device, which is of especial value where the prime requirement is to attain maximum cleanliness, is that being of such small diameter the effective efficiency of removal of impurities is extremely high. Normally 2 in. diameter cyclones could not be used on paper stock because the reject orifices clog too easily. In the Radiclone this is neatly avoided by having two inlet holes into each cyclone each of which is smaller in diameter than the reject orifice; thus large impurities which would block off the reject cannot enter the cyclone in the first place and as long as they remain in the inlet compartment it is unlikely that any restriction to flow will occur. An air bleed-off from the top of the reject compartment is also provided. The usual arrangement of reject stages for successive fibre recovery is adopted. From its design it is possible to imagine there being trouble with cleaning if pitch and slime or large impurities become lodged in the inner compartments, but this should in practice present little more difficulty than keeping pipework clean and the usual chemical methods would have to be relied on. Unfortunately, to date there have been no operational reports dealing with the application of this device to paper stock.

The principal advantage of cyclone cleaners lies in their simplicity of construction and high efficiency, though they can have several disadvantages. Larger models have a small space requirement for a given capacity, but for the smaller more efficient models a greater number of individual units is required and in conventional installations this increases the space needed. Capital cost may be slightly lower than for a comparable installation of cylindrical cleaners. Properly designed, a battery of cyclones should present little trouble in running provided attention is given to avoiding the possibility of plugging of reject orifices; if this is likely to be troublesome with the diameter of cyclone required (i.e. 6 in. or under with normal stocks) then it will be advisable to remove large impurities beforehand either in a suitable piece of screening equipment

or in a special large diameter cyclone with a reject chamber closed to reduce fibre loss to a minimum. Occasionally aeration and flocculation of stock passing through cyclones is noticeable. Power demand is large due to the high input pressure and each stage needs a pump, also rejection of fibre and particularly of loading can be a nuisance on some grades; these points are enlarged on later.

Despite these disadvantages, the superiority of cyclone cleaners in regard to efficiency is unquestioned. Apart from the wealth of experimental data that has been accumulated, numerous mill applications testifying to their high efficiency can be quoted. For example, Downey and Blake (31) assessed the dirt in paper made on three machines equipped with large-diameter cyclones and compared it with other machines making similar grades. The total number of specks counted using the TAPPI dirt count system was a third less than on the machines with no cyclones and using the PAPRIC dirt counter the reduction in large specks was between 30 per cent. and 75 per cent., and in small specks between 25 per cent. and 60 per cent. From another aspect, Graham (16) reported that replacing old screens of the inward-flowing rotary type with cyclones on a newsprint machine not only produced an obviously cleaner sheet relatively free from specks and with a higher brightness, but removal of grit particles permitted the frequency of wire change to be reduced from 12 to 18 days and the frequency of grinding calender rolls from four weeks to eight months. Even with a higher machine speed there were less breaks due to dirt and slime in the furnish. But as a matter of interest it is also worth noting that in comparison with the old screens power consumption was doubled, fibre loss increased, and capital cost 20 per cent. higher than if replacement screens had been purchased.

2B.6 2 General characteristics of cyclone separation

The consensus of opinion from numerous reports is that cyclones are excellent for removal of small heavy impurities such as grit, sand and scale, but relatively inefficient for removal of lighter, shive-like particles. It is for this reason of course that it is becoming increasingly common for screens to be used together with cyclone cleaners, since the former are regarded as necessary for removal of the shive-like impurities. The deficiency of a cyclone in this respect is due to the influence of particle shape, a topic already touched upon in the theoretical section. It is worth examining this feature a little more closely from the practical viewpoint.

A typical report on the behaviour of shives in cyclones comes from Gavelin (25) who observed a definite tendency for thick, woody shives to appear in the reject of cyclones treating groundwood while long, slender shives were predominant in the accepted stock. Unfortunately, from the point of view of breaks long slender shives especially of the larger variety are more likely to be troublesome because when deposited in the sheet in the cross direction tension on the web exerts its influence on the weakened bonding over a greater width and is more likely to cause a tear. Nevertheless some 50 per cent. of groundwood shives (separated according

157

to the standard method using a Somerville screen) were on average removed by the cyclone.

This selectivity of rejection was seen to be manifested in other ways. Tests on handsheets made from pulp that had passed through the cyclone showed that they were harder, smoother, stronger (especially in respect of tear and fold) and less bulky than handsheets made from the untreated stock. This is also shown in the tendency for short fine fibres and fibre debris to pass to the reject in preference to long, thin fibres, an advantage over screening equipment where it is the longer fibres that tend to separate to the reject. Normally a third stage reject will contain predominantly short fibres of low brightness together with pieces of bark and shives.

Confirmation of Gavelin's results are found in several other reports. For example, Andersson (6) noted that a 3 in. cyclone cleaner removed a variety of relatively homogeneous dirt very well but not shive. Fibres retained on a 20-mesh screen reduced from 60 per cent. in the feed to only 8 per cent. in the final reject from a three-stage battery. Robinson and Kingsnorth (29) found that cyclones rejected grinder grit, which is usually less than 100 micron in size, with very high efficiency but shives (assessed by the British Standard method) were removed with very low efficiency and showed only a nil to 27 per cent. improvement.

These characteristics can cause some difference in performance on different types of stock. Broadly speaking, it can be expected that the greater the quantity of short, fine fibres in the stock the higher will be the percentage of fibre rejected for a given reject orifice diameter. This increased fibre reject is shown up not by a greater flow but by an increased thickening factor, i.e. the consistency of the reject is higher. Differences have also been observed between the behaviour of stocks beaten to different degrees.

2B.6 3 Special reject devices

Even with a three-stage cyclone battery the fibre lost at the final stage can be high and when loading is used, especially in a low-retention system giving a high concentration in the breast box feed stock, the loss of this can become economically crippling (rejection in a third stage can be 50 per cent. giving an overall loss which has been quoted at 10 per cent. or more). It was realized quite early on that some means of controlling the fibre lost in the reject flow (particularly from the final stage) would be advantageous and several devices designed to do just this have appeared on the market. Other devices attached to the reject are intended primarily to prevent suction of air into the reject orifice and to remove air already in the stock. In some cases the function of reducing fibre loss and preventing air being sucked in are combined. These various devices will now be discussed.

The simplest and earliest modification to the straightforward open reject was to submerge the tip below the level of stock in the collecting trough. This prevents suction of air through the reject into the accepted stock and usually makes a small reduction in the reject of fibre (though in some circumstances fibre reject can actually increase). But the efficiency of

impurity removal is also adversely affected and with a submerged tip it is difficult to see if there is any partial or complete plugging of the orifice (though this latter disadvantage can be avoided by using a transparent reject orifice.) One manufacturer claims to overcome the drop in efficiency with a submerged orifice by using a special design of vortex finder which opens out in the shape of a bell. However, Downey and Blake (31) compared two cyclone installations on machines using the same furnish, one having normal open rejects in the third stage and the other with the bell-shaped vortex finder. Reject from the open orifice installation contained a greater proportion of fine fibres and this is possibly an indication of lower rather than higher efficiency when using the bell-shaped vortex finder.

A development of the submerged nozzle is to have the cyclone reject tips enclosed and connected together to a manifold. Pressure in this can then be regulated so that the flow is controllable and there can be no suction of air into the accept flow. The disadvantage of reduced efficiency still applies and the greater the pressure placed on the reject line the worse this becomes. Sometimes the reject is closed off altogether and a collecting chamber added at the bottom giving a similar arrangement to that frequently used with cylindrical cleaners. This certainly cuts fibre loss to a minimum but efficiency drops to only a small fraction of what it is with a normal open orifice. Such a device is used only to give a very coarse preliminary removal of large impurities.

In an endeavour to improve the performance of a cyclone Gavelin and Sikström (25, 28) developed a special device for attaching to the reject. This consists of a small chamber with one or more openings into which is injected elutriation water (fresh water or whitewater of low consistency can be used). The purpose of this is to dilute the reject flow, thereby reducing fibre content, while keeping in the impurities. The arrangement also prevents suction of air into the reject. The pressure of the elutriation water needs careful regulation: if too high the fibre loss is increased, and if too low the nozzle can plug. Optimum conditions appear to be with a reject flow of about half the quantity of water injected and tests then indicated a substantial reduction in fibre reject (more than one third) with no significant decline in the removal of specks and shives. A commercial model is now available and is frequently recommended for the final stage of a battery of cyclones. In this position any deleterious effect on the efficiency of removal of impurities should not be very important and the pressure of injection water can be adjusted to minimize fibre loss and remove any danger of plugging. It would not be advisable to use this device on the primary stage because it is probable that changes in the injection water pressure have a marked effect on the cyclone performance.

Various other methods are available for preventing suction of air into the reject and some of these are also claimed to remove free air already in the stock. All involve applying a suction to the reject orifices and are used mainly for the first stage but can also be found on other stages. The simplest device provides suction on a water ejector principle and is termed an 'eductor'. The most elaborate has the reject discharging into a common manifold to which a controlled vacuum is applied via a level-controlled

receiver and separator (similar to the arrangement used for suction boxes). The expense of the latter system is relatively high and its likely performance must be weighed against the desirability of actually removing air from the stock in the first place. As a final degree of elaboration the deculator-cleaner system with accepts discharging into a large tank under very high vacuum has been developed. With this device, which definitely removes a substantial portion of air in the stock, the rejects must also of necessity be enclosed and joined to a common manifold. Applying suction to the reject and accept lines does not apparently have any significant effect on the efficiency of impurity removal, provided the pressure drop from inlet to accept is maintained and the absolute pressure on the reject line is kept similar to that on the accept.

2B.6 4 Influence of reject diameter on performance

In the straightforward cyclone with open reject orifice, the general performance is greatly influenced by the actual diameter of this orifice. This is relevant at the planning stage of an installation and also because widening of an orifice with age due to gradual wear alters the character of the reject. In this section the influence of reject diameter will be discussed. Information presented here and in the following section represents a consensus of work reported from several sources, in particular references 3, 7, 19, 21, 26, 28, 29. The data refers to a 3 in. diameter cyclone, though the shape of the curves apply equally to cyclones of other diameters. Efficiencies have been assessed experimentally using a variety of readily identified particles such as dyed shives and sawdust, radioactively-tagged shives, ash, rubber, sand and graded grit.

With a reasonably wide orifice, the reject flow discharges in a steady spray from the bottom of the cone. As the orifice is reduced in diameter a point is eventually reached where the spray become unstable and it finally changes to an uneven and intermittent dribble. This occurs with an orifice diameter of less than $\frac{3}{16}$ in. with a 3 in. cyclone and $\frac{3}{8}$ in. with a 6 in. cyclone. If reduced further, even this flow will eventually cease. It is generally agreed that efficient smooth functioning of a cyclone is impaired when the reject orifice is reduced below the point where the discharge ceases to be in the form of an even spray; this marks the minimum acceptable flow and is generally in the region of from 2 per cent. to 4 per cent. by volume of the inlet flow depending on the geometry of the cyclone. Above this minimum, the volume of the reject flow depends closely on the orifice diameter and the relationship is such that the flow is approximately proportional to the square of the diameter, see Fig. 2.12.

When considering the efficiency with which various types of particles are rejected in cyclone cleaners, it is common to obtain either figures in the region of 80 per cent. to 90 per cent. or more, or quite low values. The reason for this is the relatively sharp cut-off of the cyclone, i.e. the sharp increase in efficiency that occurs once a given size of particle is exceeded, as shown in Fig. 2.7 on page 123. It is therefore obviously more relevant that discussion of the effect on performance of making various

alterations is centred on changes in efficiency of rejection of a size of particle which is already in the high region. Fig. 2.12 shows such a typical relationship between the reject orifice diameter and efficiency of rejection, the latter being defined as the percentage of ingoing particles found in the reject flow. As would be expected, efficiency increases as greater flow to the reject is allowed.

In cleaning paper stock, efficiency must be assessed in terms of the reduction in impurities in relation to fibre. In other words, efficiency must
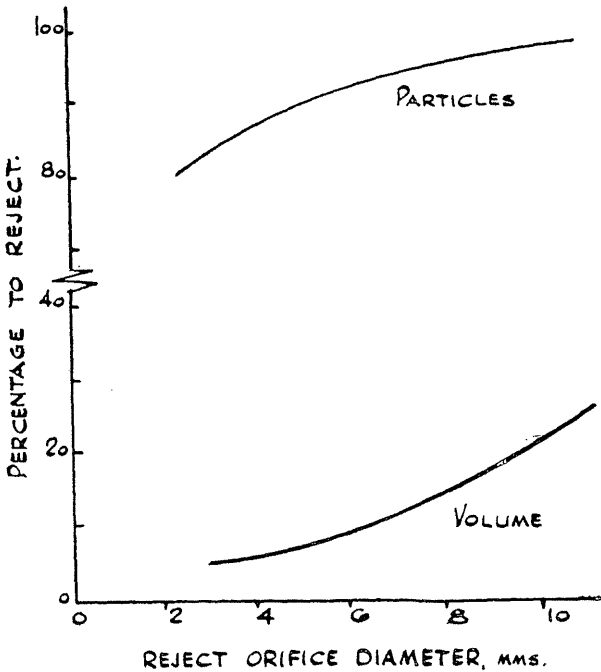

Fig. 2.12. Dependence of percentage number of particles and of flow volume to reject on the size of the reject orifice for a typical 3-inch cyclone

be calculated as the reduction in particles passing out in the accept flow per given quantity of fibre; in practice due to the relatively small change in accept flow consistency under different operating conditions, the efficiency can equally well be determined on the basis of the reduction per given volume. If the efficiency curve in Fig. 2.12 is modified to take account of changes in the volume flow to reject, the curve in Fig. 2.13 results; the difference between this based on a correct definition of efficiency and that in Fig. 2.12 which relates only to the total number of particles going to the reject is seen to be relatively small except when higher reject volumes are reached. This point can therefore be ignored without any sig-

nificant loss of accuracy though it should be noted that for lower efficiencies the difference would become greater.

At first sight then it appears that efficiency of cleaning can always be increased by opening up the reject orifice. While certainly true, in practice account must of course also be taken of the fact that fibre in the reject flow also increases as the orifice is opened up. Even with several stages of fibre recovery in an installation the fibre lost from the final stage is dependent on the fibre rejected from the previous stages, so increase in the reject diameter effectively produces a similar increase in the fibre lost from the system. A typical relationship between fibre rejected and reject orifice diameter is shown in Fig. 2.14. It will be noted that the rate of increase
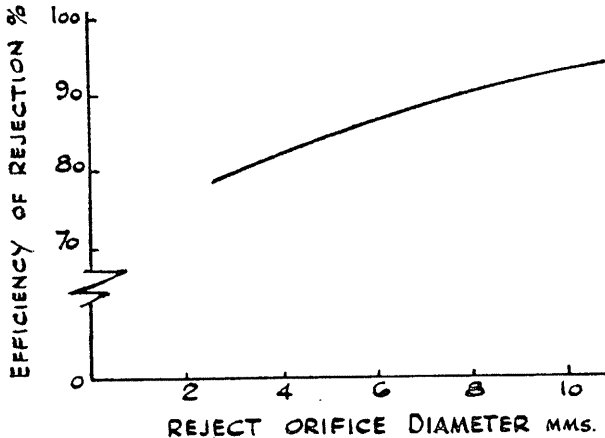

Fig. 2.13. Actual efficiency of rejection in relation to reject orifice diameter for the same 3-inch cyclone

is not so great as for the actual volume of flow rejected and this is due to the fact that the thickening factor, i.e. the value of the reject consistency in relation to that of the inlet, varies as shown also in Fig. 2.14. The thickening factor first shows a slight increase but beyond quite a low orifice diameter further increase in size of the orifice causes a gradual diminishing of the factor so that the rate of increase in fibre rejected is lower than the rate of increase of volume rejected.

It is evident therefore that an increase in efficiency is gained only by sacrificing a greater fibre loss. The relation is shown in Fig. 2.15 and the choice of whereabouts on this curve to operate obviously presents an economic versus quality problem that can only be related to individual machines. The rise in efficiency as the reject orifice is opened up from the minimum flow possible is at first relatively high, whereas the increase in fibre lost is much slower. It is reasonable on this basis to assume that most cyclone installations have a fair margin of running conditions where the reject orifice diameter can vary over a tolerable range without noticeably
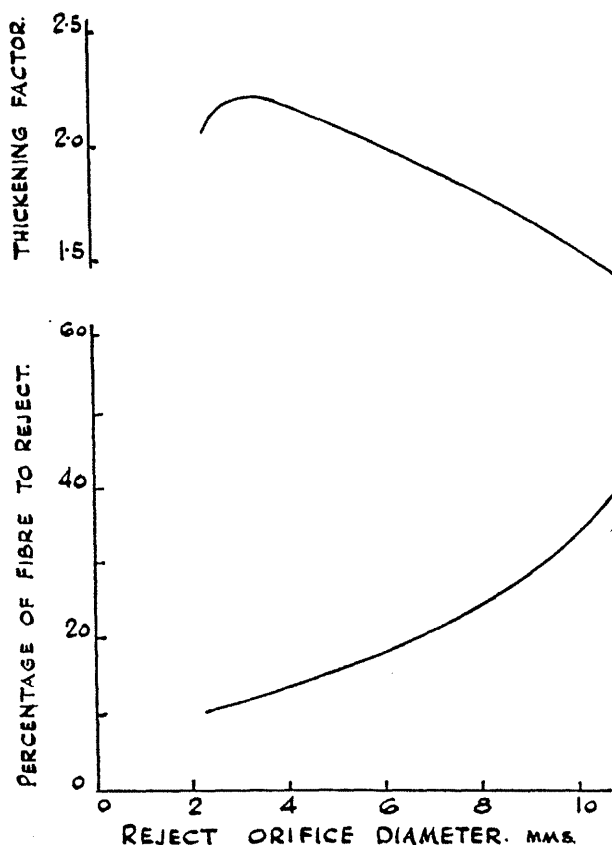
162

Fig. 2.14. Dependence of thickening factor and of the reject percentage of fibre on the reject flow from the same 3-inch cyclone

affecting efficiency. If a battery of cyclones is first installed with the size of the reject close to the minimum possible, then a reasonable amount of wear can be tolerated before the performance becomes economically inefficient due to excessive fibre loss.

2B.6 5 Influence of operating conditions on performance

There are two important operating conditions which closely affect the performance of cyclones: the feed pressure and the stock consistency. Both these variables affect performance not only in regard to the efficiency of rejection of impurities but also in respect of operating costs to deal with a given throughput of fibre. These points will now be considered.

Fig. 2.16 shows for a 3 in. cyclone the relationship with other conditions constant between input pressure and efficiency, and also between pressure and throughput. It will be observed that both efficiency and throughput increase with higher pressure but that both begin to level out in the region of 40 to 50 p.s.i., especially the efficiency. The behaviour of other characteristics is less certain as reports are conflicting in some respects, but there is evidence that with increasing pressure the percentage of flow in the reject diminishes while the thickening factor increases. The net result of this is that the fibre passing out in the reject flow shows little change with pressure.

Based on this it is generally recommended that little is gained from running 3 in. cyclones above about 40 p.s.i. inlet pressure. For larger
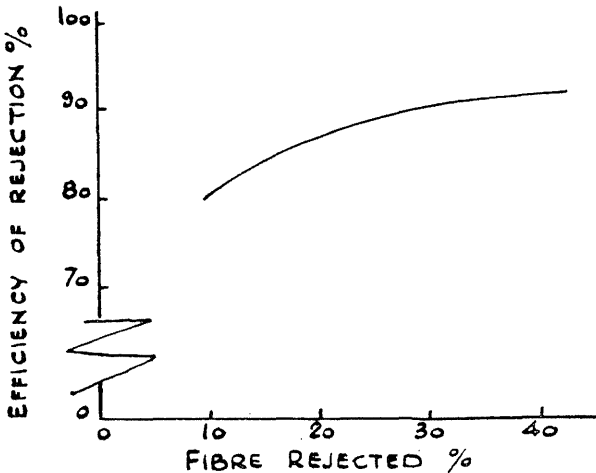

Fig. 2.15. Relationship between efficiency of rejection of impurities and the fibre lost in the reject for increasing reject flow

cyclones the optimum pressure is considered to be slightly higher though of course the efficiency level for comparable spherically-shaped particles would be much lower at any given operating pressure. Some observations by Gavelin and Sikström (28) have indicated that at lower pressures removal of specks from paper is less efficient (in confirmation of the above), but that removal of shives is better than at higher pressures.

With regard to consistency of the stock pumped through a cyclone battery, as this is increased a point is reached where efficiency of rejection of impurities suddenly drops off. This point depends on the reject diameter, the drop occurring at a lower consistency when reject diameter is smaller. The changes in efficiency are presumably connected in some way with the change in viscosity which occurs somewhere above 1 per cent. consistency and with the influence on vortex strength of the viscosity, especially

towards the apex of the cone. A typical example of change in efficiency with inlet consistency is shown in Fig. 2.17.

Also shown in this figure is the change in the percentage of fibre rejected. This is seen to have a minimum, the reason for which is somewhat obscure but appears to result from the opposition of two changes which occur
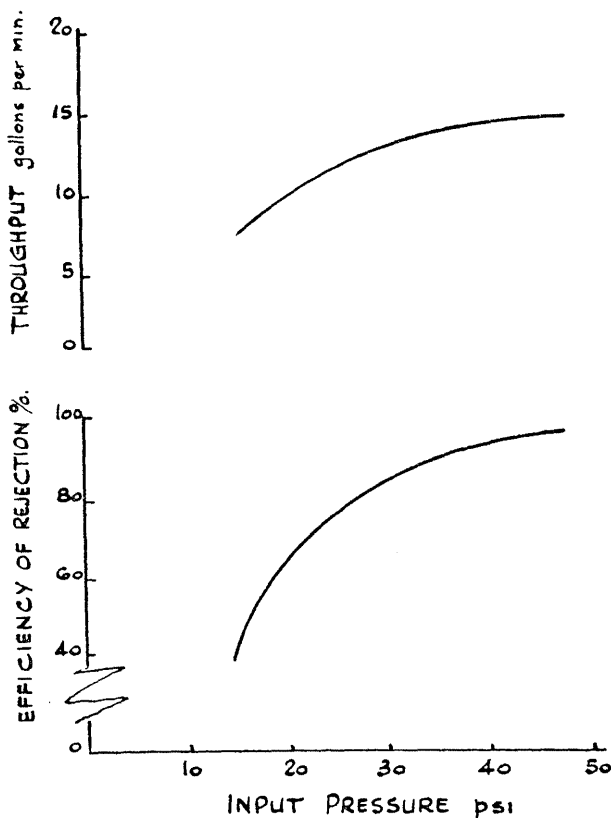
Fig. 2.16. Dependence of efficiency of rejection of impurities and also of throughput on the input pressure to a 3-inch cyclone

with increasing consistency: the thickening factor decreases, with a levelling off above about 1·5 per cent. consistency, while the percentage of flow going to the reject gradually increases with increasing inlet consistency.

The presence of this minimum implies that under any given conditions of input pressure, type of stock, cyclone geometry, and so on, there is an optimum consistency which will keep loss of fibre to a minimum. This seems to occur at a higher consistency than the point where efficiency begins to diminish sharply. The consensus of opinion on this matter is

that consistencies should ideally be kept in the 0·6 per cent. to 0·9 per cent. region for optimum performance, though this must vary with conditions and some workers notably Brecht *et al.* (19) advocate lower consistencies than this.

The consistency also has a bearing on the cost of treating a given quantity of fibre because the higher the consistency the lower the pumping
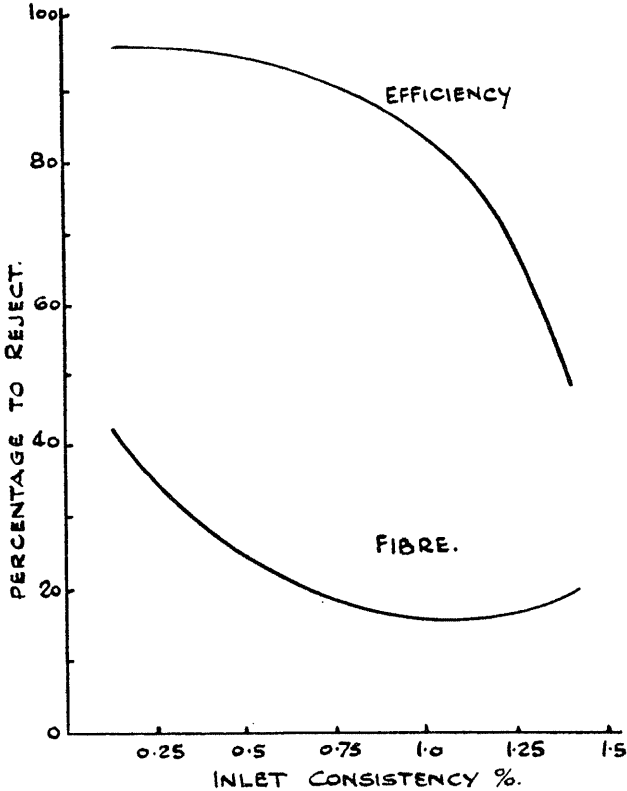
Fig. 2.17. Dependence of the efficiency of rejection of impurities and of the fibre rejected on varying inlet consistency

costs. This point has been examined by Robinson and Kingsnorth (29) in relation to the inlet pressure. Fig. 2.18 from their work gives an illustration of how the cost of pumping is related to consistency and pressure. Ideally curves of this nature need to be considered in comparison with those of efficiency of impurity removal under the same conditions.

In practice most machine systems do not permit running of stock to the breast box at a consistency selected at will, and this is in fact governed by drainage and other variables on the wire. Stock is normally fed to the

box at consistencies under 1 per cent., which from the foregoing appears quite suitable. Only for machines using breast box stock at very low consistencies, say below 0·3 per cent. or 0·4 per cent., does the fibre reject begin to get excessive and the efficiency improve little with more dilution. In such cases it can often be advisable to dilute to between 0·6 per cent.
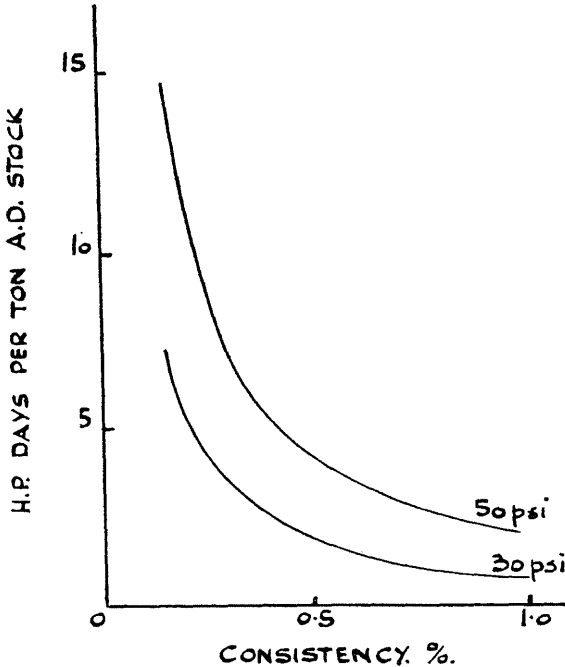
Fig. 2.18. Dependence of power requirements (assuming 50 per cent. overall pump efficiency) on operating pressure and consistency (after Robinson & Kingsnorth)

and 0·8 per cent. or so for cleaning and follow this by a further dilution before entering the breast box. This procedure would be economical anyway to reduce the size of the installation required to clean a given tonnage of fibre and to cut high-pressure pumping costs.

2B.66 Choice of cyclone size

There are on the market a range of sizes of cyclone from 2 in. diameter up to 12 in. diameter and greater. The choice of which size to use for any specific application is one of the most important decisions that have to be taken. The advantages of using a large size of cyclone can be listed as follows:

(a) the initial cost is generally cheaper because a lower number of units and less ancillary pipework, pressure gauges, isolating valves, etc., are needed.

167

(b) there may well be a fewer number of stages needed and this reduces running costs and saves the expense of an additional pump and associated pipework, trough, etc.

(c) it is often not considered necessary to provide a higher inlet pressure to larger cyclones, so that pumping costs are similar to those for smaller cyclones.

(d) the larger reject orifice diameter implies less possibility of plugging occurring.

(e) space requirement is lower.

Against these points, the principal advantage of smaller cyclones is their undoubtedly superior efficiency in removing small, heavy, spherical-shaped impurities, especially grit, ash and sand. In regard to shives, the matter is more complicated for small cyclones are less efficient than large for removing relatively large shives of a long and slender shape. This is of importance with groundwood and other furnishes used for lower grades of paper, though not if screens are used in conjunction with the cyclones. Normally it would be argued that for efficient removal of shive-like material screens are necessary anyway, as even larger sizes of cyclones have a relatively poor separation efficiency for this type of material. Thus this particular deficiency of small cyclones is relevant in only a few special cases.

A second advantage to small cyclones is that fibre loss from an installation can generally be kept lower because of the possibility of reducing the size of the final stage to treat a lower capacity than a single larger-size cyclone. However, this point is not of great importance in practice because there are other methods, as described above, of reducing fibre loss from an installation and in any case a number of small size units could be used just as effectively for this purpose in the final stage of a battery of otherwise large cyclones. Also for any given stock the thickening factor is higher for smaller cyclones and this tends to become more disadvantageous in the final stage and also to offset the advantage of smaller capacity.

Early work by Rastatter and Croup (3) established that the 3 in. cyclone was economically preferable to larger sizes from the point of view of obtaining maximum cleanliness at minimum cost. Consequently when commercial models first became available it was this size that was normally recommended for installation. Since then there has been a steady trend towards using the larger sizes of cyclones until now the 12 in. diameter is probably becoming the most popular. The reasons for this gradual change hinge on the various advantages of larger cyclones as listed above, but undoubtedly the most important factor has been avoidance of plugging. This in itself has become even more imperative because of the increasing interest in combining cyclones with devices to remove air that necessitate an enclosed reject; in such cases a plugged reject orifice cannot easily be detected and cleared so that no risk of this occurring can be taken.

Batteries of 3 in. cyclones not only contain a large number of units but in the vast majority of applications are a positive bugbear to keep running

satisfactorily. A continual inspection of the reject tips is invariably needed and can demand a great deal of the machineman's time. It is essential to have a means of rapid isolation of individual cyclones (normally by valves or cocks on each inlet and accept line) so that the reject tip can be removed, cleaned and replaced as quickly as possible. Various attempts to avoid this plugging have been made, but none have been wholly successful. The most promising was the use of a soft rubber tip which distends under pressure when the accept flow is temporarily closed off and thus blows out debris accumulated at the bottom, but in practice wear of the tip proved too much of a disadvantage. Assessment of the likelihood of plugging in any situation is difficult though as a guide it is sometimes said that this depends on the frequency of impurities greater in size than about half the proposed reject orifice diameter (an impurity does not need to exceed the orifice in size in order to cause blockage because fibre rapidly collects round a particle in the vicinity of the reject and a partial blockage can develop first before the reject stops completely). It is always of course feasible to give stock a preliminary coarse cleaning to remove impurities likely to cause plugging, though this inevitably increases the overall cost for achieving higher cleanliness.

It has also been argued by the advocates of larger cyclones that so long as the efficiency of removal of impurities is sufficiently high, there is no virtue in using the smaller diameter cyclones with their attendant disadvantages. This may well be true in some cases but it would be unusual for a mill to be able accurately to define a lower limit of dirtiness for its paper below which it did not consider it worthwhile to go. It is safe to say that most mills would prefer complete freedom from blemishes in their paper, and the smaller size of cyclone is more likely to achieve this. Further in regard to such benefits as longer wire life or interval between calender grinding, removal of really small grit probably confers as much advantage as removal of the larger pieces. So it may equally well be argued that if a mill is going to the expense of installing and running cyclone cleaners it should demand the highest practicable efficiency. For this the smaller the cyclone the better, so it is well worthwhile always to look closely at the relative importance of the various disadvantages to using the small size. In this respect the Radiclone design merits consideration as it appears to overcome several of the disadvantages mentioned above, especially that of plugging.

A final point regarding the use of small cyclones concerns paper stock with a heavily-loaded furnish. Loadings with a large particle size, particularly china clay, are rejected at a comparatively high efficiency which can mean that a heavy loss of 10 per cent. or more is sustained from the final stage of a 3 in. cyclone installation. Also when there is a low retention and breast box stock carries a high proportion of loading to fibre, the concentration of loading from one stage to the next can become so high that excessive dilution is needed, thereby increasing capital and running costs as well as fibre and loading loss due to the larger second and third stages required.

Where this is a problem it is often the case that large cyclones are the

only ones economical to run. To give some indication of the position in this respect some data given by Jacobsson (21) are worth quoting. He reports that rejection of such loadings as titanium dioxide (which has a small particle size) is in practice negligible, but for finely graded china clay the rejection in a single pass through a cyclone is of the order of 20 per cent. for a 3 in. diameter unit, 3 to 4 per cent. for a 6 in., and 1 per cent. for a 12 in. unit. If the clay is relatively coarse these percentages can rise to 30 to 40 per cent. for a 3 in. cyclone, 6 per cent. for a 6 in., and 2 to 3 per cent. for a 12 in. unit. The advantages of going to larger sizes of cyclone for stock heavily loaded with clay are thus evident.

CHAPTER 2C

RUNNING SCREENS AND CLEANERS

2C.1 DAILY OPERATION

In dealing with the running of screens and cleaners, the same procedure is followed as in other Parts of the book. Measurements required by the machineman for day-to-day operation are covered first, and this is followed by a discussion of the longer-term maintenance needed. Finally, practical aspects of running screens and cleaners are dealt with.

2C.1 1 Measurements required

Practically all the measurements required for successful operation of screens are straightforward indications of pressure. For flat and open rotary screens it is important that the pressure of sprays is measured. With enclosed screens measurement of the inlet pressure of the stock is important, especially when there are a number of units in parallel and it is necessary to adjust the flow through each to be similar. Equally it is important to measure pressure on the outlet side of a screen.

The difference between these inlet and outlet pressures is a measure under given flow conditions of resistance to passage of stock through the screen. Should this difference begin to rise this is an indication that the screen plate is beginning to clog and therefore gives the machineman early warning that action is necessary. In some cases the risk of this happening may be so high that a differential pressure gauge is considered necessary. Developing this even further, because changes in the differential pressure between inlet and outlet of an enclosed screen are relatively gradual and early detection of any trend to clogging is vital, it is occasionally thought advisable to link the reading to a recorder.

In a similar way measurement of pressures is the basis of successful cleaner operation. With both the cylindrical and cyclone type the pressure in the inlet manifold has to be measured and set to the recommended running level. Pressure in the accept must also be measured to ensure no restriction in the line is raising this above the low value usually required. This is very important because the whole action of a centrifugal cleaner depends on the pressure drop from inlet to accept. These measurements are, of course, equally essential in each stage of reject treatment.

When the rejects from a number of cylindrical or cyclone cleaners are connected together then measurement of pressure on this particular manifold is necessary to ensure it does not rise above the recommended minimum. This is especially important when the line is operated under vacuum. The pressure of whitewater or fresh water used for dilution between stages of an enclosed system must also be measured to permit

171

flows to be balanced. This applies too to water used for elutriation or vacuum ejector purposes.

Finally, the power required to operate a screen is of obvious importance, especially for enclosed screens where the power to rotate the impeller can be a useful indication of any tendency for the plate to clog or the level of stock to be low inside the screen. The power used by pumps in cleaner installations must also of course be measured.

2C.1 2 Control applications

There are very few control applications vital to the operation of screens and cleaners though they are becoming more common. The flow from the reject of a primary enclosed screen to a secondary has to be kept steady and this is one area where a number of automatic control mechanisms have been introduced. Straightforward pressure control on the reject valve would be possible but this method has not found favour because the basic problem here is to prevent the valve itself from gradually becoming plugged due to the relatively high consistency usual with an enclosed screen reject. The most favoured approach has been to use a special type of automatic valve which can be opened momentarily and then returned to its original position; this is controlled by a conventional timing mechanism which allows both the frequency and the period of opening to be set as desired. There are various techniques used for this purpose, some of which are applied also to the periodic opening of screen traps and the collecting chambers of cylindrical cleaners. The same principle in reverse has been used to close temporarily the accept line from cyclones in order to raise pressure in the unit and blow out any debris collecting in the reject orifices.

Occasionally control systems involving the pressure drop across cleaners are used. These usually work on a re-circulation line from the primary accept back to the inlet, this flow being regulated to keep the pressure drop constant. With open-reject cyclone units discharging into troughs, the level in these is kept steady by controlled addition of dilution water.

When vacuum is applied to the reject line of cleaners it is generally governed by a straightforward automatic control, especially when a pump is used. Level control in the vacuum receiver tank would also be usual. Similarly vacuum and level controls are used when vacuum is applied to the accept of a cleaning installation, as for example with the deculator-cleaner system.

2C.2 MAINTENANCE

2C.2 1 General maintenance

Apart from general engineering maintenance and lubrication which will be the responsibility of the engineering department, the main attention the papermarker must give to screening equipment is to keep it clean and check the screen plates for fracture and wear. Cleanliness is covered in 2C.3. With regard to the screen plates, it is important that each is given

a careful examination every shut period. With the open rotary and flat type this involves little more than a visual examination and inspection of holding bolts and sealing strips. To inspect the enclosed screen necessitates removal of the cover and for this reason it is preferable to have the cover fastened with swing bolts and suspended from a davit arm. Any fractures or holes in the plate means immediate replacement to prevent large impurities or fibre and slime lumps passing through.

Wear of screen plates occurs over a long period so that a regular three- or six-monthly check of the size of slits and holes is a useful precaution. Slots that start off at, say, 18–20 thou will widen steadily and the point at which replacement is necessary, 25 thou or even 30 thou, must depend on assessment of the deterioration in terms of performance. Several positions should be checked at random in the screen for this purpose, taking care that separate plates are each checked individually. With the enclosed screen, holes in different parts of the compass should be checked as wear is not always even.

Other points of maintenance of screens depend on the type in use. Scrapers on certain types of flat screen must be checked periodically for contact with the surface. On the inward-flowing rotary screen the sealing strips at the ends of the screen should be examined regularly. These frequently need quite a lot of attention to ensure a good fit. No bolts should be missing from the plates. The screen plates themselves occasionally need a thorough cleaning with acid or some other suitable chemical compound depending on whether they are subject to corrosion or scale build-up.

With regard to centrifugal cleaners of the cyclone type, the main maintenance necessary is change of the reject orifice tips when these become over-large. Generally, this becomes evident when fibre loss has increased to an unacceptable degree, but it is worthwhile periodically to measure the orifice diameter of several or all cyclone units and keep a record of the readings. Wear takes place more rapidly in the later stages of a battery, especially the final stage which of course is mainly responsible for the fibre loss, so cyclones in this position require frequent checking depending on abrasiveness of the stock.

Occasionally a complete cyclone should be dismantled and inspected because wear and scale build-up can affect the inside surface. This can reach the stage where a regular spiral groove from the inlet to the reject orifice is visible and there is no doubt that this impedes efficient removal of impurities. Close to the reject orifice a number of deep circular grooves are sometimes cut in the body of the cyclone where a large abrasive particle has spun round for a long time. Once such a groove is started it tends to collect and hold further particles, thus accelerating the wear. This is a region where flow should be very smooth and is therefore particularly sensitive from the point of view of efficiency. Generally all that can be done in cases of bad wear is to re-line or replace the whole cyclone.

Cylindrical cleaners do not require a great deal of maintenance other than occasional changing of the reject diaphragms which gradually wear. Each unit should be dismantled at intervals to inspect for roughness and pitting of the surface.

2C.2 2 Long-term records

Keeping a check on the long-term performance of screens and cleaners is obviously important but unfortunately it is one of the most difficult tasks to do with any accuracy. The main purpose of both screens and cleaners is a negative one, to remove from the stock impurities which are likely to give trouble and cause downtime from one cause or another. Accordingly their efficiency depends in the first place on how big a job they have to do at any particular time. A dirty batch of pulp can cause havoc on the paper machine, but the screening and cleaning equipment may be nonetheless functioning at the usual level of efficiency which just happens not to be good enough to cope satisfactorily with this particular situation. In a similar way there are generally seasonal variations in pulp and this too can affect the apparent efficiency.

Ideally it would be preferable to be able to measure the efficiency at intervals to provide long-term records of performance. But enough has already been said about the problems of doing this with a mill installation to make it obvious that any direct test is out of the question. Records of such things as dirt counts on the web or on sheets, reels rejected or sheets sorted out due to impurities, breaks of the web suspected as being caused by lumps, and even of wire life where an abrasive stock is concerned should all in theory give some indication of changing efficiency. But these are also affected by so many other factors that in practice it would appear highly unlikely that any direct change in efficiency of screens or cleaners can be detected by this means.

Turning specifically to screens, provided the slit and hole sizes in plates are measured regularly this would appear to be the most useful check on likely performance variation that can be carried out. It is also useful to take samples from the inlet and reject of screens, both primary and secondary, to assess the consistency and loading changes that take place; on some types of stock fibre fractionation and freeness figures can also give valuable data. The reject flows should be measured, as should the flow and consistency of any spray water. Together with measurements of flow, consistency and so on taken throughout the wet-end flow system (as discussed in 1C.2 3), a fairly complete picture of performance can be built up. Comparison over a long period of results obtained in such checks gives useful confirmation of any trends likely from wear of the screen plates.

Similar checks are necessary for cylindrical and cyclone cleaners. Here samples from the inlet and reject of each stage and of dilution water should be taken and checked for consistency, loading and possibly also for fibre fractionation. Flows through the system can be easily calculated but a check on the actual flow of dilution water to each stage or the whole installation is useful for confirmation. Where elutriation water is used, the flow of this too should be measured.

Of particular importance is the flow from the final stage since this will almost invariably represent loss from the system. Checks of the flow, consistency and loading content of this loss should be carried out more

regularly than would be usual simply for the purposes of long-term records which are at present under discussion. At least once a week is advisable if the loss is not suddenly to be discovered much higher than was thought. It is also essential to check this loss on each major grade of paper made because it can vary considerably, especially with loaded stock, from one furnish to the next.

Sheets can be made from the reject of the first and later stages of a cleaning installation and from the reject of a screen for the purpose of visual examination of impurities. But this is not advisable because interpretation of any differences observed is very tricky. Even with the same grade of stock and, as near as can be arranged, the same flow and pressure conditions, the reject can vary greatly in impurities. Certainly this is true in regard to the actual quantity of impurities present, if only because this depends closely on the amount of fibre being rejected at any given time. About the only use such sheets can have is to illustrate at any time the sort of impurities that are present in the stock. This is of course quite different from giving some indication of efficiency.

2C.3 PRACTICAL POINTS

2C.3 1 Start-up

The exact starting-up procedure for a screen depends on the method used for the wet-end as a whole. If the machine wire pit is filled with fresh water and this is pumped round the system first, fresh stuff being gradually added when everything is already operating, then few problems are likely to arise. Whether open rotary or enclosed screens are used, these are started immediately before the mixing pump discharge valve is opened. Power consumption is then checked and where sprays are used these are turned on. The vibration mechanism and sealing strips of an open screen should be examined. Reject valves are set in their usual operating position. With an enclosed screen the air bleed-off is opened.

As soon as stock starts coming through, the action of the screen must be carefully watched. An open rotary screen should present a completely clean appearance at the top with no areas where fibre is left hanging. Also the level in the vat should be stable. With an enclosed screen the only indication that all is well comes from checking the pressure drop between the inlet and outlet. The reject flow to the secondary screen is adjusted as necessary and when a non-clogging valve is used this is switched on.

When the breast box stock has approached normal running conditions, just before the web is fed over from the couch, screens should be given a final check-over. This is to ensure that they are coping all right with the increase in consistency that occurs as a growing quantity of fines re-circulate in the backwater. The spray water is turned over either manually or automatically to whitewater. When there are several screens in parallel the stock should be evenly divided between them; this is assessed either visually with open screens or from the relative pressure drop across enclosed screens.

In older systems, particularly those using a mixing box, it is customary to turn water and fresh stuff on together so that the first flow fed to the screen contains stock at near normal consistency. This can happen too, of course, if there has been a temporary shut on a machine and the back-water pit already contains stock. The danger here is that the initial rush of stock is at a relatively high consistency and in this event immediate clogging of the screen plate may well occur. To avoid this there should always be a delay after starting the system up before the fresh stuff is turned on. With enclosed screens provision is sometimes made to fill the screen with water before the impeller is started and stock admitted. Both these precautions should make clogging much less likely.

Secondary screens are of course started at the same time as the primary and sprays, dilution water, and power consumption checked. With the open flat screen the vibration mechanism and, when used, the scrapers should be examined. Once flow of stock from the primary reject starts to come through to the secondary screen the operation requires more attention. Generally, however, there is little point in setting dilution water to the secondary screen and adjusting the sprays to give the reject desired until flow at the wet-end has settled down. Secondary screens of the flat type can often be tricky to set satisfactorily so this is probably best left till the machine is under way.

A cleaning installation comprising several stages of cyclone or cylindrical cleaners does not generally require the same care in starting as screens do provided a standard sequence of operations is followed. Dilution water is first turned on and, with the conventional cyclone set-up, troughs allowed to fill with water. When appropriate, elutriation and 'eductor' water is turned on and the pump on a reject vacuum line started. The procedure then is to set the final stage going first, then the previous stage, leaving the primary stage until last. The sequence must be carried out reasonably quickly, as there may be an insufficient capacity of dilution water available to keep the stages filled, so normally it is not commenced until immediately before the stock is ready to be delivered from the mixing pump.

Each time a stage is started pressures on the inlet and (when enclosed) on the reject lines are adjusted if necessary. Note must also be taken of the accept pressure because any restriction in this line causing an increase in pressure will reduce efficiency considerably. When a vacuum pump is used on the reject or accept line the gauge on this and the level in the receiver are checked. Occasionally a re-circulation line is used to balance out flow to the cleaner installation and operation of this to keep the accept pressure at the usual level must also be correct. It is always prefer-able to design the system so that only a single valve on the discharge side of each pump has to be opened, leaving all other valve settings unaltered from previous running. This is because it is easy particularly with a totally enclosed system to upset the balancing of flows to different stages.

Once stock has approached equilibrium conditions the cleaners should be examined carefully. Stock building up in closed reject chambers and discharging from the final stage of a cyclone battery should be checked

and the dirt content noted. Especially at start-up there can be a large accumulation of impurities which necessitates early cleaning out of closed reject chambers unless these are emptied automatically. The reject nozzles of smaller diameter cyclone cleaners are particularly apt to plug at start-up and when this occurs there is an immediate drop in efficiency of the cyclone unit concerned. Unplugging cyclone reject orifices can be a very demanding task for the first few hours after start-up.

2C.3 2 Shut-down

Before shutting down screens and cleaners it is always best if backwater or fresh water is pumped through to prevent thick stock lodging anywhere in the system. The best method of shutting the wet-end is to close the fresh stuff line and run the fibre out on the wire to the hog-pit, allowing the backwater in the machine wire pit to be pumped round for a short time; if this procedure is followed then it should suffice to clear the screens and cleaners of fibre. Otherwise fresh water should be run through.

Open rotary screens should be rotated for some time with the sprays on and then thoroughly hosed down with a high-pressure jet. Enclosed screens sometimes have facilities for back flushing and this is effective for clearing screen plates. Even so every enclosed screen unit should be opened up and the impeller examined (taking special note of the gap between the impeller heads and the plate) and the visible part cleaned out with a jet. Unfortunately, it is not generally possible to give an enclosed screen a thorough clean without actually removing the plates so periodically this should be done also. Apart from this attention screens need little in the way of regular maintenance so far as the papermaker is concerned. With inward-flowing rotary screens the sealing strips should be carefully checked. The trash-collecting chambers of enclosed screens have to be emptied and swilled out.

Cleaners of the rotary centrifugal type require a really thorough hosing out after the main body of fibre held in the various compartments has been dug out. Cylindrical and cyclone cleaners cannot be cleaned inside so it is particularly important that water with low fibre content is pumped through before the installation is shut. The first stage is then shut down, followed by the second and so on. Open troughs are washed out and with some models of cyclone cleaners the nozzles can be taken off and cleaned if this is usually necessary. Apart from this no other action is needed.

2C.3 3 Checking screens and cleaners during running

Normally screening equipment requires little attention while running. With the open rotary type an occasional check must be made that the rotating and vibrating mechanism is alright and that level in the vat and flow from the reject are satisfactory. Most attention is probably needed to the sprays which should always completely cover the length of the cylinder. When whitewater is used a partially blocked spray is more likely and this leaves a ring of uncleaned screen plate which eventually becomes made up, thus effectively reducing the screening area available. Sealing strips and spray troughs should also be inspected.

With the enclosed screen there is little examination possible other than to check that the inlet and outlet pressures are normal, the power consumption at its usual level, and the reject flow steady. When a continuous air bleed from the top of the screen is used this must be examined as the valve will frequently tend to get made up due to the low flow. Compartments catching large impurities must be emptied with reasonable regularity.

Flat screens can require more attention because they are generally fairly sensitive to changes in flow and dirt content of the inlet stock. Frequent inspection is advisable or it will be found that the reject has suddenly increased to a high level and a considerable quantity of fibre is being put down the drain. Flat screens, particularly when used in a secondary position, should be cleaned at least twice a shift, the vibration mechanism checked and other points such as the sprays and action of scrapers examined. Unfortunately secondary screens of the flat type are very often placed in out of the way positions and tend to be ignored by machinemen. This does nothing to improve an already dismal performance.

Centrifugal cleaners of the cylindrical type with reject collection compartments have to be emptied at intervals. Sight glasses are usually provided to assist in deciding when this is needed, but it is probably best for the machineman to get into a routine of emptying once or twice a shift to avoid neglect. Cyclone cleaners of small diameter will need frequent attention to the reject orifice tips to avoid plugging. Provided quick-action valves or clamps for the inlet and accept pipes are available so that isolation of the cyclone is simple, cleaning out a reject nozzle need not take long. Occasionally it should be possible to clear out a nozzle simply by temporarily closing the accept line thus putting the full pressure on to the reject. Otherwise inspection of cylindrical and cyclone cleaners is confined to checking over the various pressures through the system. When vacuum is applied to accept or reject lines, the functioning of this system also requires occasional examination.

There are always periods on any machine when impurities of one kind or another appear in the paper or cause breaks. It is at such times that the screening and cleaning equipment is the first to be scrutinized. Once it has been thoroughly checked over and no faults can be seen, the machineman is naturally at a loss to know what to do except blame the pulp, which he usually does. Occasionally, of course, this proves to be a correct accusation, and then little can be done except either re-circulate more stock flow round the screens and cleaners (when this is possible) or divert secondary accept flow to the preparation system in the hope that some impurities will be broken down to a more acceptable level.

A laboratory analysis of impurities appearing in the paper can be very valuable to give a clue as to the source of trouble. It is after all always preferable that impurities are eliminated at source rather than to depend on the screens and cleaners to remove them. There are one or two other actions that may be taken. Holes and slots in screens and cleaners can be checked (particularly if this is not done on a routine basis). The fresh water and backwater lines can be opened to see that they are not a source of contamination from rust, scale, slime, etc. Additive systems, especially

of loading when this is placed in slurry form into the mixing box or pump, are also worth checking over. There are usually many places where dirt and slime can lodge in open tanks, the breast box, vacuum receiver tanks and manifolds, and so on. Such positions should be gone over with a tooth comb. Finally, of course, there is always the possibility that the impurities are getting into the paper at a later stage by falling from the roof on to the wire, being picked up by felts at the press, or coming from the drying cylinders and felts. If an analysis is made of the impurities in the first place, this should serve to narrow the field and enable attention to be confined to those parts of the system most likely to yield up the culprit.

REFERENCES

(1) Chester, C. A.: 'A Study of the Operation of Sand Tables.' Proc. Tech. Sec. **31**, 3, 617. November, 1950.
(2) Minute, A.: 'Modern Methods of Cleaning Paper Stock.' Proc. Tech. Sec. **33**, 1, 29. February, 1952.
(3) Rastatter, E. L., and Croup, A. H.: 'Hammermill Dirt Separator.' TAPPI **35**, 5, 223. May, 1952.
(4) Steenberg, B.: 'Principles of Screening System Design. Studies in Screening Theory I.' Svensk Pap. **56**, 20, 771. October 31, 1953.
(5) Almin, K. F., and Steenberg, B.: 'The Capacity Problem in Single Stage Screen Cascades. Theory of Screening II.' Svensk Pap. **57**, 2, 37. January 31, 1954.
(6) Anderson, D. D.: 'Centri-Cleaning of Sulphite Pulp.' TAPPI **38**, 9, 183A. September, 1955.
(7) Stockman, L., and Ruus, L.: 'Cleaning of Pulp with Cyclones.' Svensk Pap. **58**, 15, 483. August 15, 1955. (In Swedish).
(8) Boadway, J. D., and Freeman, H.: 'Centrifugal Classifier for Cleaning Pulp and Paper Stocks.' TAPPI **39**, 11, 797. November, 1956.
(9) Gorham, A. B.: 'Reducing the Dirt Content of Unbleached Sulphite Pulp with Centrifugal Cleaners.' TAPPI **39**, 7, 199A. July, 1956.
(10) Smith, J. A., and Stewart, J. C.: 'The Deculator—Cleaner Process.' TAPPI **39**, 3, 198A. March, 1956.
(11) Wenberg, H. B.: 'Nicolet's Experience with the Vorvac System.' Paper Trade Journal **140**, 5, 34. January 30, 1956.
(12) Brown, A. D.: 'Cleaning of Board Furnish with Vorject Cleaner and Vortrap Classifier.' Canadian Tech. Sec. Proc. p. 381. 1957.
(13) Casper, R. R.: 'An Investigation of Centri-Cleaner Performance using Radioactive Tracers.' TAPPI **40**, 5, 175A. May, 1957.
(14) Dyson, A. O.: 'The Vorvac, Vorject and Vortrap as applied to the Paper Machine.' TAPPI **40**, 1, 136A. January, 1957.
(15) Espenmiller, H. P., and Zuehlke, E. H.: 'The Shartle Liquid Cyclone—A Centrifugal Cleaner.' TAPPI **40**, 1, 140A. January, 1957.
(16) Graham, W. M.: 'Centrifugal Cleaners on a Newsprint Machine.' Canadian Tech. Sec. Proc. p. 387. 1957.
(17) McLean, J. A.: 'Use of Miami Selectifier Screens for cleaning Stock Supply to Newsprint Machines at Great Northern.' Canadian Tech. Sec. Proc. p. 360. 1957.
(18) Nuttall, G. H., and Hendry, I. F.: 'Design and Coupling of Cyclone Installations.' TAPPI **40**, 12, 951. December, 1957.
(19) Brecht, W., and Weishaupt, K.: 'The Suitability of a Hydracyclone for Pulp Screening.' Woch. fur Pap. **86**, 7, 221; **8**, 281. April 15, 30, 1958. (In German.)
(20) Corte, H.: 'Calculations of Screening Systems.' Zellstof und Pap. **7**, 4, 116. April, 1958. (In German.)
(21) Jacobsson, J. J.: 'De-aeration of Paper Stock with or without Cleaning.' TAPPI **41**, 5, 179A. May, 1958.
(22) Nuttall, G. H.: 'The Use of Cyclones for Cleaning Pulp and Paper Stock.' Paper Maker **135**, 3, 230; **4**, 326. March and April, 1958.
(23) Salomon, S., and Lukianovitch, S.: 'The Application of the Bird Centriscreen on Newsprint Furnish.' P. and P. Mag. Can. **59**, 7, 111. July, 1958.
(24) Tirado, A.: 'Theory of Screening.' TAPPI **41**, 5, 235A. May, 1958.
(25) Gavelin, G.: 'Shive Content Reduction of Groundwood Pulp by Centrifugal Cleaning.' Svensk Pap. **62**, 10, 355. May 31, 1959.
(26) Kemp, G., and Rance, H. F.: 'Hydraulic Cyclones in the Cleaning of Papermaking Stock.' Proc. Tech. Sec. **40**, 1, 53. February, 1959.
(27) Klinga, I.: 'The Design of Hydrocyclones for the Paper and Pulp Industries.' Svensk Pap. **62**, 1, 11. January 15, 1959. (In Swedish.)

(28) Gavelin, G., and Sikström, L.: 'An Investigation of Two Hydrocyclones for Groundwood Pulp.' Svensk Pap. **63**, 11, 398. June 30, 1960.

(29) Robinson, W., and Kingsnorth, S. W.: 'The Cleaning of Paper Stocks with Particular Reference to Development of a New Screen for Sisal Removal.' Paper Technology **1**, 6, 635. December, 1961.

(30) Buglass, J.: 'Cleaning Stock for Esparto Papers.' Paper Technology **3**, 6, 565. December, 1962.

(31) Downey, C., and Blake, M.: 'Newsprint Stock Cleaning at Bowater's, Newfoundland.' P. and P. Mag. Can. **63**, 12, T-587. December, 1962.

(32) Hopkins, R. M., MacPherson, R., and Morin, L. J.: 'Analysis of the Effects of Centrifugal Pulp Cleaners and Pressure Screens on Newsprint Runability.' P. and P. Mag. Can. **63**, 12, T-563. December, 1962.

(33) Anon.: 'The Radiclone—A New Type of Centrifugal Cleaner.' Paper Trade Journal **147**, 52, 22. December 30, 1963.

(34) Lambert, J. E.: 'The Comparative Evaluation of Screens and Screening Efficiencies.' P. and P. Mag. Can. **64**, 9, T-406. September, 1963.

(35) MacMillan, F. A. *et al.*: 'Shives in Newsprint: Their Detection, Measurement and Effects on Paper Quality.' P. and P. Mag. Can. **66**, 7, T-361. July, 1965.

(36) Sears, G. R. *et al.*: 'Shives in Newsprint: The Role of Shives in Paper Web Breaks.' P. and P. Mag. Can. **66**, 7, T-351, July, 1965.

PART 3

THE WIRE SECTION

INTRODUCTION

3I In Part 1 the characteristics of the Fourdrinier paper machine were considered up to the point where the stock passes through the slice. General features of recirculation in the main backwater system, the retention of fibre and loading, and the use of whitewater from the suction boxes and couch were also discussed. It is proposed now to cover the wire section itself from the point where the stock impinges on the wire to where it is couched off the wire. Certain subjects which have already been considered in the context of the overall wet-end flow system, for example breast box stock consistency and temperature, are now treated from the point of view of drainage and formation of the sheet on the wire. Attention is confined to the basic Fourdrinier design; sheet forming in cylinder vats, rotary formers, combinations with Fourdrinier wires for duplex and other special types of paper, the use of secondary headboxes, or such relatively new processes as Inverform, Twinverform, or Verti-forma are not considered.

In the first few feet of the wire the most important structural features of the web are determined and the main object of the machineman is always to achieve as good a formation as possible, in the general sense of the term. This subject is dear to the hearts of every papermaker and ideas abound of what happens at this crucial stage of the papermaking process. There is also a considerable difference between opinions of what constitutes a good formation, particularly when the term is applied to newsprint and tissue on the one hand and to fine papers made on slow machines on the other. Some attempt is made to clarify this whole problem in the light of observations obtained in recent research but it must be emphasized that probably in this sphere more than any other it is not yet possible to talk in terms of a theory as such; generalizations can only be made with extra care.

Throughout the length of the wire drainage of water from the sheet is taking place, and this comprises the second main purpose of the wire section. Drainage and formation are closely connected in the sense that satisfactory conditions for the one are no use at the expense of the other; the machineman must constantly compromise between having adequate dilution of the stock in the breast box to form the sheet and sufficient capacity on the wire to drain the sheet adequately. Accordingly, close consideration is given in the text to the manner in which drainage of the sheet occurs, both in the table roll section and at the suction boxes.

When the sheet is sufficiently dry it must be transferred from the wire to the press section where removal of water by pressing becomes more efficient and economical than continued application of suction in the boxes or couch. Transfer cannot occur efficiently before the sheet is strong enough to withstand the stresses involved and, since the wet strength of the web increases with dryness, this usually means that the sheet is run as dry as possible into the presses to avoid breaks. This is generally beneficial due

185

to the fact that when the sheet is drier entering the presses, it will be drier entering the drying section where removal of moisture is relatively costly. But on the other hand additional dryness at the couch is usually obtained during day-to-day operation either by reducing the consistency of stock in the breast box, and thereby affecting formation, or by applying more vacuum in the suction boxes, thereby affecting the power consumption and the life of the wire. Each of these factors has to be carefully balanced and, as in so many aspects of papermaking, some compromise in operation has to be found.

The couch itself extracts water and so affords an additional means of reducing the moisture in the sheet before it is couched off the wire. But other factors are involved here and the couch is, or should be, primarily designed to facilitate the actual removal of the web from the wire. In this sense the extraction of water, though an extremely valuable corollary of the couch operation, should not be allowed to prejudice the successful transfer of the sheet.

These are the main aspects governing the general operation of any wire section. In addition, the wet strength of the web at the couch and the overall quality of the paper is affected in some degree by the compaction to which the web is subjected on the wire. The vacuum applied to the suction boxes and the pressure and vacuum at the couch are significant in this respect, but the most important influence comes from the operation of a dandy. The compacting action of the dandy inhibits subsequent drainage from the sheet (as is readily observed from movement of the dry-line position when a dandy is raised from the wire) and thereby affects both the stock consistency which may be run in the breast box and the dryness at the couch.

These brief remarks serve to emphasize the interactions occurring between the various factors which influence operation of the wire part on a machine. They also serve to show the complexity and difficulty of assessing the function and performance of each section of the wire part and illustrate why the design of this part of a new paper machine remains above all a purely empirical process relying almost entirely on analogies and extrapolation from the performance data of existing machines. What follows represents an attempt to set down the more important features governing this section of the paper machine; as in other Parts of the book, the method of presentation involves division of the material into three basic chapters, though it must be admitted that in this case it has not always been easy to distinguish between what, because of its fundamental and general nature, comprises theory, and what should rightly be treated as one of the factors influencing operation. The author hopes that the division actually chosen does not appear too arbitrary.

CHAPTER 3A

THEORETICAL CONSIDERATIONS

3A.1 DRAINAGE IN THE TABLE ROLL SECTION

On slow machines running a relatively heavy substance, drainage in the table roll section is largely a continuous process by gravity; the pressure of water in the fibrous mat on the wire is sufficient to overcome the resistance of surface tension forces within the wire meshes and natural drainage through the wire occurs between the table rolls. On very slow machines this can result in a flow down the leading side of the table rolls, similar to that occurring in a plain press, as water carried on the underside of the wire is compressed between the wire and table roll. Under conditions of gravity drainage the mesh of the wire and the consistency, porosity and thickness of the mat must be particularly important in determining the rate of dewatering.

With increase of speed the time available for gravity drainage between the table rolls diminishes and dewatering of the web by this means becomes rapidly insignificant except in the region where the stock first meets the wire. Instead it is readily observed that drainage occurs almost exclusively on the trailing side of the table rolls. All experimental work on this subject reported in recent years has concerned faster machines with this form of drainage at the table rolls, and what follows is confined to this aspect.

3A.1 1 Suction developed at a single table roll

At one time it was considered that surface tension forces were responsible for pulling water out from the web on the trailing side of a table roll, but in the early 1950's it became clear that this force was inadequate to explain the quantities actually discharged and that separation of the roll and wire surface in fact produced a suction force on the web. Several investigators approached the problem of elucidating the nature of this suction force both from the experimental and the theoretical angle and as a result of their efforts though many details remain unexplained an adequate general picture can now be given.

Direct measurement of the suction force has been attempted by Bennett (9), Burkhard and Wrist (21), and Mardon and his colleagues (67). This is an extremely difficult task though the results of Burkhard and Wrist, obtained by attaching a specially designed piezo-electric pressure transducer in the body of a table roll on an experimental machine, are sufficiently reliable and consistent to give the general pattern. Typical curves for different machine speeds obtained by these investigators are illustrated in Fig. 3.1 and show the pressure or suction exerted on the table roll surface as it passes under the wire.

187

The interpretation of these curves by the authors, based additionally on observations and photographs of the relevant part of the wire section, is as follows. The first small rise in pressure as the gap between the roll and wire is closing is caused by water carried into the nip; this has a relatively small
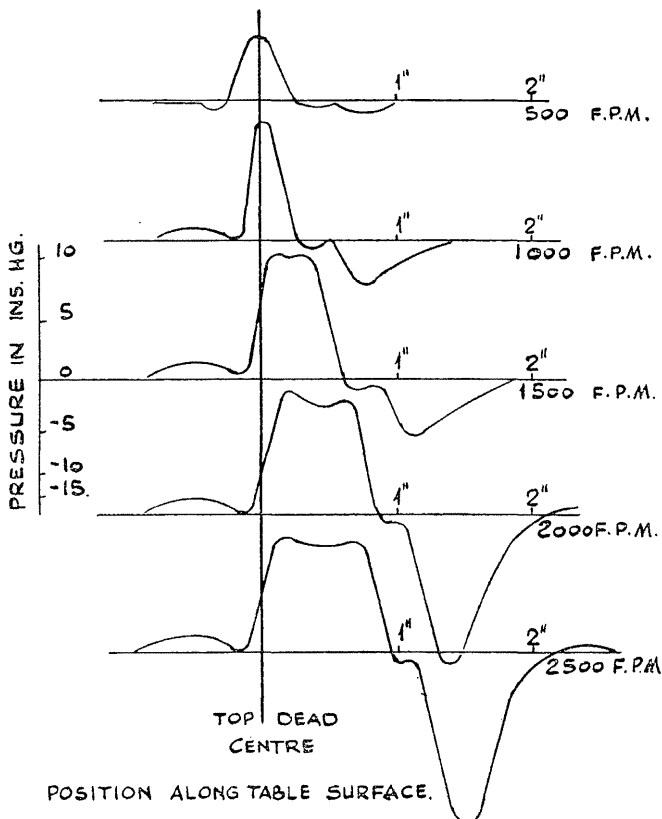

Fig. 3.1. Pressure exerted on table roll surface as it passes under the wire at different machine speeds (after Burkhard and Wrist)

effect (though in this work the table roll was doctored) but causes the mat on the wire to lift very slightly. From the point where the wire meets the roll, just before top dead centre, round to where contact is broken, there is a region of high pressure; this corresponds with an area where the stock level on the wire is observed to rise and then dip as the wire wraps round the table roll on the trailing side. The length of this region clearly increases with speed due to the greater wire wrap which occurs with the development of higher suction forces once the wire has left the roll. The length was

shown to depend, as expected, on the tension in the wire, decreasing with increased tension; also to a lesser extent the length decreased with increasing drainage resistance of the mat caused by, for example, a drop in temperature or rise in consistency or substance of the mat. The magnitude of the pressure also appeared, up to a point, to depend on the speed, though the development of the double peak is not explained.
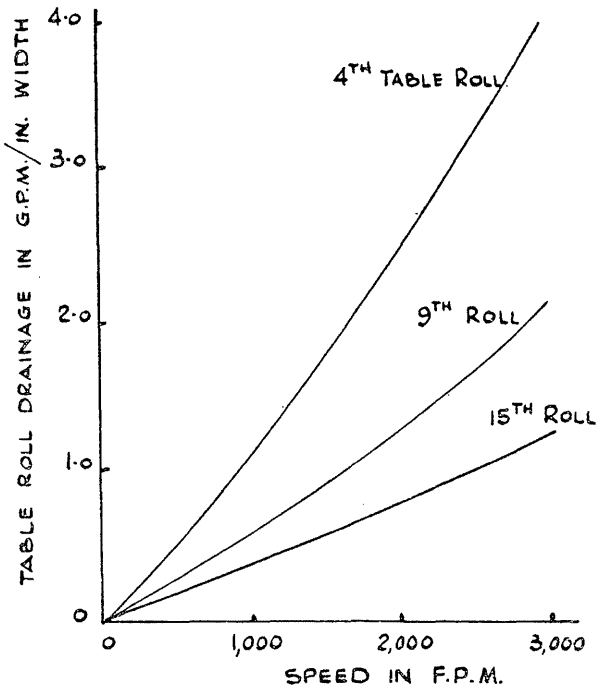

Fig. 3.2. Drainage at three different table roll positions for varying machine speed (after Wrist)

After the pressure region a small plateau occurs where pressure is approximately zero as the web begins to leave the roll; the suction region then commences with pressure rapidly falling to a minimum followed by a slow subsidence. The peak magnitude of the suction depends closely on the speed and was shown to increase in value at a rate almost proportional to the square of the speed. As the length of the suction region also increases slightly with speed, this and the lower suction peak have a combined effect in increasing the total quantity of water discharged.

3A.12 Discharge from a table roll

The relationship between quantity discharged and speed is of great importance in papermaking, but unfortunately the precise relation is not easy to

determine experimentally due to the difficulty of keeping other conditions constant, particularly that of the drainage resistance of the mat above the table roll. Fig. 3.2 shows a graph given by Wrist (84) and illustrates how for a groundwood/kraft furnish the discharge at three different table rolls down the wire increases with speed, the relationship in this case being such that the discharge is proportional to the 1·2th power of the speed, i.e. the discharge increases at a faster rate than the speed. Unfortunately this result cannot be generalized for Tellvik and Brauns (62) in similar work obtained a power of 0·3 for kraft stock, which implies a substantially reduced increase in discharge for proportional increase in speed, although they also obtained the same power of 1·2 for a newsprint furnish.

Although the mat conditions on the wire complicate the issue, it is evident that the quantity of water removed by a table roll will be dependent in some way on the total suction applied in the nip, i.e. the integrated value of the suction over the length of its application. Thus, as a first step in any theoretical approach determination of both the magnitude and shape of the suction curve are important and a great deal of effort has been directed towards establishing these, notably by Cowan, Wrist, Meyer, Bergström, and particularly Taylor. An extensive summary and analysis of the work of these authors has been given by Mardon *et al.* (67) and it is not proposed here to consider the subject in any detail, though a few general comments on the methods used will be made.

3A.13 Taylor's theories of table roll discharge

There are two main theoretical derivations which are usually taken as a starting point for checking against experimental results and these are based on radically different hypotheses as to the nature of flow in the table roll trailing nip. In the first of these it is assumed that no mixing or turbulence occurs and the flow is taken to be completely streamline; in the second case complete turbulent mixing is assumed to take place in such a way that the velocity at any point in the nip depends only on the gap between the wire and the roll. Both these theories were first conceived and applied by Taylor and each gives a suction curve similar in the general sense to that determined experimentally by Burkhard and Wrist. There are however, two main differences between them: firstly, the no-mixing hypothesis predicts a lower value for the maximum suction in the nip (though in both theories the peak suction is shown to be proportional to the square of the speed and therefore agrees reasonably with experimental observations); secondly the suction region extends further along the table roll in the case of the turbulent mixing hypothesis. The net effect of these differences is that the turbulent mixing hypothesis predicts a discharge from a table roll equivalent to 2·5 times that predicted by the no-mixing hypothesis.

This may appear such a great difference that there should be no difficulty in deciding which theory agrees closest with observations. It has already been mentioned, however, that the quantity of water discharged by a table roll depends not only on the suction applied to the web but also on the resistance presented by the mat itself to the passage of water through it.

The main difficulty is, therefore, that there is no initial absolute comparison to act as a standard and it is only possible, in the absence of data directly relating to the drainage resistance of the mat under the particular conditions pertaining, to compare the discharge of one roll with another. Attempts have been made actually to determine the drainage resistance of a fibre mat under different conditions and these will be considered in the next section.

It should also be possible to decide between the two theories by direct measurement of the peak magnitude of the suction in the nip but according to Mardon evidence in this direction is, at the moment, contradictory. Thus, although the turbulent mixing theory is most favoured in that it is considered likely to express closer the actual hydrodynamic conditions in the nip, the choice remains open. Several attempts have been made to modify and compromise between the two basic approaches; Bergström for instance has produced corrections covering the degree of wrap by the wire round the roll, but these need not be considered here. It may be noted, however, that Taylor has been able, with the aid of some fundamental experimental work, to show that the curtain formation which is such a common feature of drainage at a table roll is due basically to the instability arising from the separation of two surfaces carrying a fluid.

The object of this work is partly, of course, to account for the total drainage in a wire section and also for the variation in the quantity of backwater drained at each table roll according to its position along the wire. Accurate predictions of the effect of altering such things as the length of the wire table and the number and diameter of the rolls may then be possible. This has become more imperative as the speed of machines has been increased to the point where considerable difficulty may be experienced in giving the sheet reasonable time to form while removing the water in a practicable length of wire at the same time. For this reason considerable attention has been concentrated on examining changes in the drainage properties of the mat as it progresses down the wire and in the discharge from the individual rolls. This topic will now be considered in some detail.

3A.1 4 Variation in drainage resistance of the mat down the wire

One approach to the problem of determining how the resistance to drainage of a mat varies with its changing condition down the wire is to attempt to measure it in a simulation experiment. This has the advantage that the effects of different properties of the fibres and water comprising the web, the degree of beating, temperature, addition of fines and loading, etc., can be investigated at the same time; this in turn may help to establish some fundamental conceptions of what determines drainage resistance and explain why with different stocks on the same machine variations occur between the quantity drained at one part of the table roll section compared to another. Laboratory simulation can also indicate how drainage resistance depends for different pulps on the weight of the mat already formed on the wire and on the amount of suction applied (the

latter is particularly important in the application of drainage theories for it enables the rate of movement of the water under a given suction to be calculated).

In this field Hendry *et al.*, Ivarrson and Johannson, Ingmansson, Higgins and de Yong, and, for simulation of higher speeds, Meadley and Anneus have done useful work; for details reference can again conveniently be made to the survey by Mardon *et al.* (67) in which the results of some of their own work are also presented. More recently Wahlström and O'Blenes (83) have reported results obtained with a specially modified apparatus designed specifically for simulating drainage conditions close to those appertaining on the wire; they found that the rate of mat formation and drainage is very dependent on pulp type and the degree of beating while neither the concept of specific drainage resistance, which has proved useful for low consistency work, nor the freeness test is related to the drainage rate figure obtained in their work. Boadway and Gray (85) have also reported work in which the drainage resistance of the fibre mat both vertically and horizontally, and of the wire itself, have been estimated separately; they suggest that the structure of the wire has an important influence on the drainage resistance of the mat and does not act simply as an extra resistance to drainage in addition to that of the mat itself.

It is evident from this that the factors affecting the flow through a compacting mat of fibres on a wire mesh are extremely complex and this is no doubt the reason why up to the present time little useful progress has been made in predicting theoretically the variation down the wire of the quantity of water extracted at the table rolls. Some typical curves of this variation are shown in Fig. 3.3 and were obtained for different speeds by Tellvik and Brauns (62); in addition curves giving the change in consistency of the table roll discharge are shown. These results were obtained on an experimental machine and no changes were made in the pulp and making conditions other than that of speed.

3A.1 5   Predicting drainage conditions on a machine

Using data on the variation of discharge from individual table rolls on a wire and making assumptions about the manner in which the average drainage resistance varies down the wire, both with the suction applied and the thickness of the formed mat, it is possible to determine which of the two basic theories (mixing or non-mixing) mentioned above best fits observations taken under different conditions; Mardon and his colleagues used this approach amongst others but found fundamental differences between the results for newsprint and kraft stock and once again obtained no clear-cut indication as to whether either theory is likely in general to be correct.

Tellvik and Brauns, on the other hand, used their data as a starting point to determine what influences the drainage resistance through the settled mat of fibres formed on the wire, and, by assuming this resistance to be dependent only on the mat properties and independent of speed, determined how the flow from the table rolls would vary with speed if other
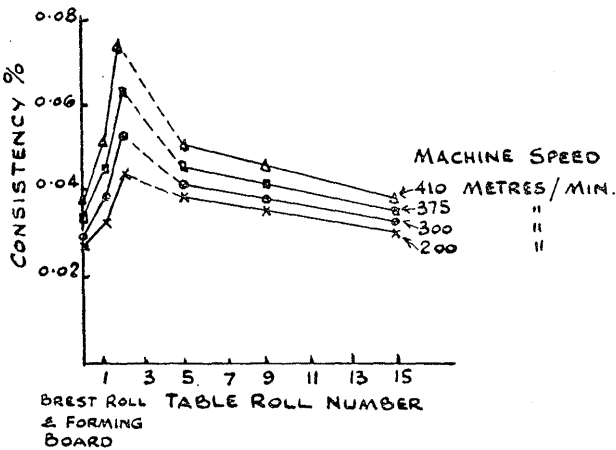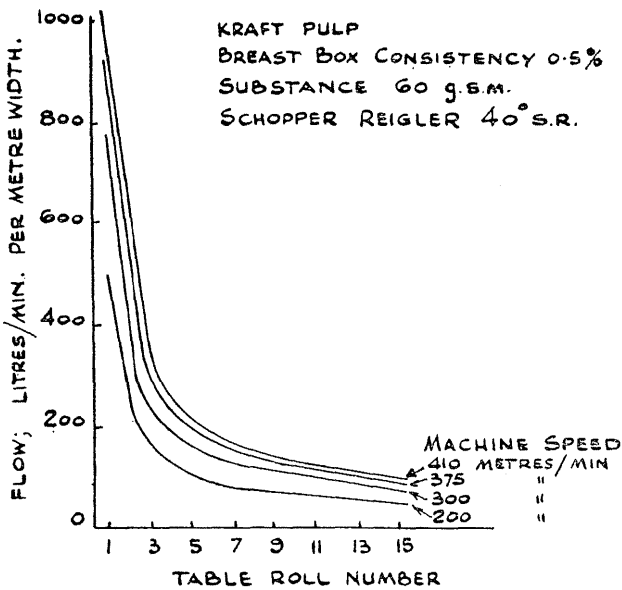
Fig. 3.3. Flow and consistency of discharge from table rolls at different positions down a wire and at different speeds (after Tellvik and Brauns)

193

factors remained constant. This proved radically different for two different types of stock due probably, it is suggested, to a difference in compression of the settled fibre mat on the wire; in fact, as mentioned earlier, the influence of speed for a kraft as opposed to a newsprint furnish was small and the magnitude of the drainage for kraft was determined more by the weight of the fibre mat and slowness of the furnish. Although these authors claim that on one particular machine operated with a constant type of stock it is possible to take certain measurements under operating conditions which may be extrapolated to predict the effect of a change, insufficient is yet known about the detailed mechanism of drainage for any generalizations to be possible.

3A.1 6 Bennett's observations

It is appropriate at this point to mention in more detail some results reported by Bennett (9) in which the quantity and consistency of discharge from the table rolls of a newsprint machine were, together with much other data, measured on several occasions. The flow from the table rolls declined down the wire in exactly the same manner as Tellvik and Brauns have shown in Fig. 3.3; also the consistency of the discharge was at a maximum at the second table roll (though in this case the breast roll and first table roll discharge were not sampled separately). The decrease in consistency of the discharge (which incidentally applied mainly to fibre— the ash content did not alter appreciably down the wire) is readily explicable in terms of the filtering effect which occurs as the mat builds up in thickness; the increase in consistency occurring in the early part of the wire may be attributed to a greater reduction in the quantity of water as opposed to fibre discharged, although the behaviour of the table roll flow in this region before the mat has fully formed must be highly dependent on the forming conditions.

Bennett and his colleagues also analysed statistically the effect of varying several conditions on different regions of the table roll part of the wire; the variations were such as occurred during normal production and so in all cases the range is comparatively small. Increasing speed over the range 610 to 690 f.p.m. appeared to increase the flow proportionately greater in the early positions (i.e. the speed had less effect down the wire), and the net effect was that the consistency of the mat at the first suction box was relatively unchanged. An exception to this was the combined breast and first table roll discharge, which was apparently unaltered by the speed; this may be due to the fact that at this part of the wire substantial gravity drainage occurred and the proportionate reduction of this with increasing speed offset the increased drainage produced by the rolls. But on the other hand the suggestion has been made that the slice jet may have impinged further down the wire at the higher speed and reduced the effect of the breast roll discharge. Again it can only be said that conditions in this part of the wire are highly critical and generalizations are probably very risky; other aspects of this topic will receive consideration in later sections.

Other results obtained by Bennett indicate that an increase in temperature

of the stock, while generally increasing the flow from the table rolls, causes a greater proportional increase further down the table. This has been considered reasonable on the grounds that flow against capillary forces (such as occurs through the thick mat more towards the end of the table rolls) is related to surface tension, and this is affected by temperature more than the purely hydraulic flow which predominates in the first few feet of drainage area on the wire. The freeness, drainage time, and consistency of the breast box stock did not appear to have any significant effect on one part of the table roll section as opposed to another though there were indications that an increase in consistency retarded drainage more in the earlier part of the wire.

3A.2 FORMING THE SHEET ON THE WIRE

The term 'formation' is used in a variety of senses in the paper industry. In a general context it may be applied to describe the overall quality of the sheet as gauged by looking through it; in this respect it can amongst other things cover freedom from pinholes, blotches, light patches produced by splashes and bubbles on the wire, streaks, worm marks, and even absence of dirt and slime particles. In fact, in this most general sense any aspect of the sheet originating in the wire section, at least up to the point where the sheet is fairly well compacted, could be included under the heading of 'formation'; the term then has a different emphasis of meaning according to the common faults encountered in the particular mill where it is used.

At the other end of the scale, 'formation' is used to describe the homogeneity of appearance when viewing the sheet in transmitted light. This restricted sense is nowadays in more common use and will be adopted here. It thus covers the terms 'wildness', 'cloudiness', etc., applied to describe the presence, size and frequency of clumps of fibres or areas of thicker concentration in the sheet; as such the formation is essentially dependent on the manner in which the stock is lead through the slice, deposited on the wire, and then drained, without reference to other defects which may exist.

In what follows an attempt will be made to describe recent thoughts and theory on how the sheet is deposited and formed on the wire and how this influences the formation. It is convenient at the same time to include two other aspects of this complex subject, two-sidedness and fibre orientation, since both of these properties are established at the same time as the formation and governed by the same general conditions. The influence of various factors such as the shake, wire mesh, relation between velocity of the slice jet and wire speed, and dandy on these properties of the sheet will be given individual attention in the appropriate place later.

3A.2 1 The nature of formation

Except for certain specialized papers it is generally agreed that a sheet of paper should be as homogeneous as possible. This implies a completely

even distribution of long and fine fibres and loading throughout the volume of the sheet and a paper approximating to this ideal will have an excellent formation. In practice, formation is assessed subjectively by the machine-man from observation of the sheet held up to a light to compare the light and dark patches; the information gained from this examination is supplemented by following the sheet down the wire by eye to assess the degree and manner of small scale movement occurring as the fibres settle into a mat (at least on machines running at most 1,500 ft./min.). Altering the formation on the basis of this information may justly be termed, perhaps above all else, the art of papermaking, and the steps taken on any particular machine to remedy or improve some aspect of formation often seem to be completely individual to that machine and to depend on a wealth of accumulated experience in running the particular paper and wire section.

In an attempt to achieve some degree of objectivity many instruments have been devised for the purpose of assessing formation in some measur-able terms. An excellent summary of the investigations made in this field has been given by Robertson and Mason (81), to which reference may be made for further details. Most of the instruments are, of course, essentially laboratory devices for examining and analysing variations in the light transmitted from varying sizes of slit through a single sheet of paper. An essential point of the design of these instruments is to check how results derived from the light measurement correlate with subjective assessment of the ranking of a variety of papers having different formation; in some cases elaborate attempts have even been made to take account of the behaviour of the human eye. Some models have now been placed on a commercial basis and may be purchased.

There have also been some reports, notably by Robinson (23), Maclaurin (58) and Eastwood (87), of the application of a formation measuring device actually on the machine at the dry-end, and attempts have even been made to use the readings obtained to regulate refiner settings. The merits of this latter step are debatable since refining is only one of the factors which have a bearing on the formation of a sheet, but nevertheless this does represent a worthy move to place control of the property on a more systematic basis.

Apart from optical methods of measuring formation use has been made of alpha, beta, and gamma radiation from radioactive sources to measure very small-scale substance variations in a sheet of paper, notably by Brazington and Radvan (43), and Attwood and Parker (71). This is doubtless a valid approach, since optical and substance variations must be closely correlated, and in fact this could eventually prove to be a more suitable and useful means of assessing formation.

At this point it is worth emphasizing that the line dividing formation problems from those of relatively small-scale substance variation is not clear-cut. Generally speaking, it is convenient to think of relatively small substance variations as one of the causes of such faults as cockling: thus, the areas of lighter substance dry faster than the heavier and shrink, causing the damper and more plastic parts of the web to become stretched

and dried under tension; the lighter and less strained areas of the sheet will then (as discussed in greater detail when dealing with drying) have a greater stretch under a given tension and a greater moisture expansivity, particularly if the paper is liable to shrinkage, and in reaching equilibrium with the atmosphere by relaxation and re-gain of moisture cockling may occur. Formation differences, on the other hand, may be considered to be confined to areas so small that differences in drying do not have a significant effect on structural properties of the sheet. Nevertheless in extreme cases the difference in thickness over a small area between different parts of the sheet can become noticeable not only as poor formation in the look-through of the sheet but also in the surface characteristics, since the thicker portions become more glazed in the calenders.

3A.2 2 Factors contributing to the formation

In the strict definition of the word, good formation depends on achieving a regularly ordered deposition of fibres on the wire. It is usually considered that, in a general sense, this is best achieved by ensuring two things. Firstly, that the discharge from the slice is as homogenous in distribution of fibres as possible and in this context this implies, above all, no flocculation. Secondly, that there is sufficient small-scale agitation of the stock when it is on the wire to preserve this state until the fibres are set in the mat. A third important aspect is that the impact of the jet and wire should not be disruptive in character though a certain degree of turbulence in that area may help to complete the even distribution of fibres; as this is largely a negative effect it is more appropriately dealt with later in 3B.1.

While this theory is no doubt substantially correct (though not of much direct value in overcoming poor formation in any particular circumstances) it is important to remember that on all but very slow machines the sheet is formed in the same way that the drainage is accomplished, in a series of diminishing surges. The quantity of fibres fixed at each roll into the existing fibre mat diminishes down the wire and at each successive roll the layer deposited is thinner. Each layer is deposited in a predominantly horizontal direction, and drainage is essentially one of gradual filtration through a mat of fibres already thickened, except possibly in the later stages beyond the table rolls (see, for example, references 116 and 117). It is now proposed to examine this whole subject in detail with particular emphasis on some recent work in this field which has contributed to understanding the processes affecting formation.

With slow machines it is considered that screens of various design perform the important function of deflocculating the stock, a task which is especially vital with longer-fibred rag finishes, while the shake on the wire ensures that the fibres are kept adequately distributed until they settle into the mat. Whether or not the screens do other than keep tangled strings of fibre out of the stock flowing to the breast box need not be considered here; a great deal must depend on the nature of the flow system and the furnish and, in particular, on the rate at which the fibres reflocculate in the conditions pertaining. Regarding the shake there is

strong evidence to show that formation can benefit in comparison with an unshaken condition; however, on the subject of shake more than any other it is extremely difficult to generalize and a detailed consideration of this topic is left till **3B.3**.

One observation which is of interest is reported by Judt (48). If drainage of the pulp is delayed, by removing one or more table rolls, then on a fairly slow machine without shake the formation deteriorates. Other workers have noticed a similar effect and it has also been stated that the increased cloudiness is predominantly on the top side of the sheet. This is confirmed by the work of Luhde (112) who has demonstrated that flocs are more prominent on the top side of a sheet, though the effect diminishes at higher speeds. The usual explanation of this is that as the sheet progresses down the wire the stock still in suspension has more time to flocculate and is less subject to the shear forces induced in the wire side by the action of table rolls and other dewatering devices. In addition, on machines with shake the influence of this is also gradually diminishing.

Recently the manner in which the stock first contacts the wire, particularly with regard to the quantity drained by the breast roll, has been investigated by Manson (90) using a formation tester. Quite small alterations in the position, horizontally and vertically, of the straight slices on an old machine running at 130 feet per minute were shown to have a substantial effect on the formation, a confirmation of the importance of the stock condition as the mat first sets on the wire.

3A.2 3 Formation on faster machines

Similar but more comprehensive work has been done in this direction on faster experimental machines and there are indications that other aspects become more important at higher speeds. For instance, Parker (68) has reported that the substitution of low-vacuum suction boxes for table rolls in the wire section considerably worsens formation. This is despite the fact that under these conditions the flow on the wire is practically free from the normal disturbances which plague high-speed operation, in fact almost glassy in appearance, and small-scale substance fluctuations are considerably reduced. In this case there is no question of delaying drainage as in the work reported by Judt (though earlier drainage may well have been slower than normally occurs) so the explanation for the deterioration in formation cannot lie entirely in the increased time in which the sheet is allowed to form on the wire. Though Parker agrees with the theory that the formation is dependent on how the rate of drainage compares with the rate at which flocculation occurs, he considers that the production of controlled turbulence before the slice (usually with a perforated roll) to keep the fibres adequately distributed is less important than ensuring there is sufficient small-scale turbulence in the immediate drainage zone where the sheet is formed. In particular, he considers on the basis of the experiment mentioned above that table rolls induce such a turbulence to the stock on the wire and therefore are important for obtaining good formation as well as draining the sheet.

Wrist (84) is in general agreement with the contention that inducing a deflocculated condition in the slice jet is of less importance than has been hitherto considered. His work on perforated rolls (though other workers disagree with this, see 1B.5 3) has indicated that they do not effectively deflocculate fibres in suspension; any micro-turbulence induced by the roll decays so rapidly that reflocculation occurs almost immediately, certainly by the time the jet contacts the wire. The production of some small-scale turbulence on the wire, especially in the immediate drainage zone where the sheet is largely formed, is therefore of great importance though it must be kept to a suitable level; this turbulence, by inducing relative motion between the undrained stock and the deposited fibres, produces a combing and shearing action which inhibits flocculation. The main problem is, however, that the same turbulence if excessive will cause the overall fibre distribution to deteriorate (as happens, for example, if the shake is too hard) and it is difficult to obtain the beneficial flocculation-preventing turbulence without at the same time increasing the substance variations.

In the discussion following this last paper further evidence of the importance of table roll action in helping formation is presented. In the same work by Parker already referred to, the experiment of reintroducing some table rolls ahead of the suction boxes proper was tried; an improvement in formation over that obtained with no table rolls was observed. In addition table rolls appeared to improve formation compared to grooved rolls which are known to disturb the stock on the wire less as well as extracting less water from the sheet. The general conclusion is that some agitation to the stock on the wire is necessary during the forming period if adequate deflocculation, and consequently good formation, is to occur, and this is conveniently provided by normal table rolls.

Also in the discussion of Wrist's paper it is pointed out that the differing drainage conditions in the various experiments involving removal of table rolls would produce different retention conditions which in turn would affect the consistency of the breast box stock once equilibrium conditions for the normal substance were achieved. The suggestion was made that these variations in consistency may have been at least partly responsible for the differences observed in formation. This is a valid criticism since consistency of the breast box stock has an important effect on formation. At the moment then there is some possibility that the observations described are capable of a different explanation.

Before turning to consider in more detail the effect of breast box consistency on the formation it is worth drawing attention to some other evidence of the agitation induced in the fibre mat by table rolls. Several workers have measured the consistency of the discharge from various drainage devices under the wire and in all cases it has been observed that if a table roll follows a foil or grooved or dandy-type roll then the consistency of discharge rises at the table roll. Measurements quoted by Hendry *et al.* (3) for a tissue machine generally show this increase, and Burkhard and Wrist (21) give results for an experimental machine in which after passing over 13 foils the consistency of discharge rose at the first table roll

and continued to rise up to the third before declining. These observations suggest that solid table rolls have a substantial loosening effect on the under-side of the fibre mat and as this action would generally aid deflocculation it provides support to the theory that their operation is advantageous to the formation.

3A.2 4 Effect of breast box consistency on formation

It is well-known by machinemen that in running the wire section a com-promise is always necessary between the rate of drainage and the formation. With any particular furnish the quantity of backwater in circulation is set to give a workable position of the dry-line; in other words as much back-water is used to dilute the fresh stuff as can be comfortably drained away, leaving the moisture in the sheet at the couch satisfactory for transfer from the wire. The lower the volume of backwater in circulation, the higher the consistency of the stock in the breast box; so if the stock on the wire works wetter, i.e. drains slower, reduction must be made in the backwater volume resulting in a higher consistency in the breast box.

A higher consistency of stock in the breast box produces more floccula-tion and an increased network strength of the fibres deposited on the wire, which results in a deterioration in formation; Wrist and Norman (115) have confirmed this by demonstrating that the random variation in sub-stance of paper over small areas is greater at higher consistencies, while Schröder and Svensson (106) have presented a comparison of formation at two different consistencies which also shows deterioration at the higher con-sistency and in addition indicates a lower general strength and stretch. At really high consistencies it becomes impossible to make a sheet that is not like a snowstorm in appearance. Thus, if stock becomes wetter the machineman has a choice between risking an excessive number of breaks at the couch due to higher moisture, or shutting off backwater and allowing the formation to deteriorate. The usual remedy is to reduce treatment of the furnish so far as possible to make the stock run more free but this, if taken to excess, inevitably affects the quality of the paper from the point of view of strength, bulk, surface characteristics, and freedom from larger shives.

With the gradual speeding up of machines the point is frequently reached where the difficulties in draining the stock adequately to achieve the required quality becomes a real problem. Increasing the vacuum on the suction boxes or the pressure at the couch inevitably produces a reduced wire life and can only be taken so far without becoming economically ruinous. Alternatively, the drainage rate can be improved by such expedients as increasing the number of table rolls, using deflectors touching the wire between rolls, and increasing the flow of water removed by the breast roll; the danger in some cases, particularly with the latter expedient, is that if the drainage in the early part of the wire is too rapid flow instabilities become less controllable and wire mark more prominent, resulting in a generally poorer sheet and making the situation no better. This is the case especially with fast draining newsprint and tissue stocks and will be con-sidered in more detail later.

3A.2 5 Two-sidedness; Hansen's experimental work on loadings

All papers exhibit two-sidedness to a greater or lesser degree and in most cases it is an undesirable characteristic. The difference between the two surfaces is present even with glassine and persists after supercalendering, as an excellent series of light micrographs obtained by Emerton and his colleagues at the British Paper and Board Research Association shows (72). Wire and felt marks contribute to two-sidedness but the basic cause, and the one which is considered here, is due to variations in structure and composition through the thickness of the sheet which manifest themselves by producing different surface properties on the two sides. These variations can also affect the relative moisture expansivity through the sheet causing one side to expand or contract more in the presence of a change in moisture equilibrium than the other. This phenomenon is commonly exhibited after drying in the form of curl, but as this particular subject is more closely associated with differences in fibre orientation, consideration of it is left till a later section, 3A.2 11.

Several techniques have been used to investigate the variation in composition within a sheet of paper, the most common involving stripping off successive layers of fibre with adhesive tape, grinding or scratching off layers with fine carborundum paper or a razor blade, or using a microtome to cut very thin sections. These methods have enabled several workers to show that differences in average fibre length, loading, the proportion of one type of fibre to another, and even the frequency of air bubbles (16) can exist through the thickness of a sheet of paper. The average fibre orientation can also vary (this will be dealt with in 3A.2 10), as can the frequency of flocs or fibre clumps through the sheet (as described in 3A.2 2). With the aid of a light microscope it is possible to examine the structure in microtomed cross-sections of paper with considerable detail, and studies with this technique demonstrate the manner in which a sheet is built up from successive layers of fibres (116).

The first experimental results of some value in elucidating the basic causes of two-sidedness were obtained by Hansen (1) and are worth considering in some detail. In this case different amounts were ground off the surface of sheets of paper and ashed, enabling the distribution of china clay through the thickness of the paper to be determined. Distribution curves for paper made under different conditions on an experimental machine, but with the same basic furnish, were obtained in this manner; for example, Fig. 3.4 shows how the shape of the curve alters as the substance is increased (and the machine speed reduced approximately *pro rata*). In a different experiment it appeared that adding Sveen glue or altering the speed, though affecting the overall retention as discussed in describing the factors affecting the wet-end flow system, did not significantly alter the shape of the distribution curve.

The curves in Fig. 3.4 indicate that change in substance does not appreciably affect the percentage of filler at the two surfaces, only the inner part of the sheet changes and evens out to a steady value as the substance increases. In some cases the percentage of filler on the top side is consider-

ably greater than in the breast box stock though this increase towards the top side appears to be caused mainly by the dandy, a subject which will be covered later.

Hansen also ran the machine with doctors on the table rolls to reduce the volume of water carried into the nips; this had no effect at all on the distribution curve. In another experiment the machine was stopped with
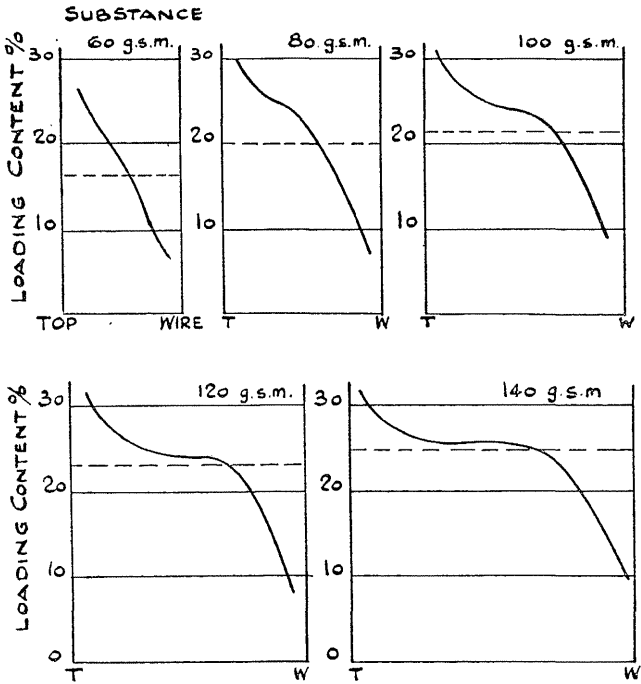

Fig. 3.4. Distribution of loading through thickness of paper made at different substances. Dotted line indicates average content (after Hansen)

the stock on the wire and then left to allow the water to drain away; the same distribution curve appeared even in samples taken just after the slice before the mat had passed over a table roll. Other experiments showed no change occurring in the shape of the curve at the suction boxes or presses and as a result of all this evidence Hansen reached the conclusion that the loading distribution is fixed when the stock has been run on the wire. The low loading content on the wire side may in fact be attributed basically to the natural process of drainage, particles of filler having less opportunity to drain out with the water through the fibre mesh as the mat grows.

3A.2 6 Other experimental work on loading distribution

This explanation has been contested by Underhay (15) who tried various methods of laboratory simulation of drainage to obtain a difference between the top and wire side loading content similar to that commonly observed in machine-made paper. In this work the main method was to split the sheet into four thicknesses and make a straight comparison of the ash percentages in the upper and lower portions. It was found that the only way in which the composition and appearance of the sheet could be made similar to machine-made papers was by applying a vertical oscillating movement to the drainage machine wire. On the basis of these observations, together with evidence that the difference in loading content between the two sides is not present in paper made on very slow machines, Underhay considered that only a 'washing' and disturbing action to the underside of the sheet at the table rolls could account for the loss of loading and fines which occurs there.

A similar approach, this time involving simply splitting of the sheet and ashing the two portions, was used by Pritchard (29) on relatively thick and heavy machine-made papers. This yielded some rather peculiar results in that there appeared to be more loading on the top than the wire side for 135 and 270 g.s.m. papers but less for 220 and 250 g.s.m. papers. Also differences were found in the relative loading content of the two sides from the couch down through the presses, and there were indications that more loading is removed from the side in contact with the felt during pressing. The order of accuracy and repeatability of the results quoted by this author appear high despite the fact that they are based on quite small differences in ash content, and with the aid of laboratory work on handsheets some attempt is made to explain the various phenomena which were found. For example, it was demonstrated that the relation of top to wire side loading content depended on the interaction of the degree of beating of the furnish and the substance and this is explained in terms of the relative ease with which loading settles through the fibres during the drainage process. Though highly interesting it is unfortunate that most results obtained in this work only permit the loading content of the two sides to be contrasted and little information is available as to the relative distribution through the sheet. It does appear, however, that for fine, heavy papers different mechanisms may come into play and this should be borne in mind in what follows.

3A.2 7 Groen's observations

The results obtained by Hansen, Underhay, and Pritchard which have now been outlined are in many cases contradictory and this largely remained the situation until Groen reported some further work (75). This involved stripping off thin layers of fibres using adhesive tape and with this technique the loading distribution of numerous papers, both machine-made and hand-sheets, was determined. In all cases the general characteristics of the distribution curve for Fourdrinier papers follow those found by

Hansen; in some there is a gradual increase in filler content from the wire to the top side of the sheet but more commonly when no dandy is used the percentage increases from the wire side until a plateau of steady value is reached, while close to the top side the percentage may show a small decrease. The shape of the distribution curve does not appear dependent on the fibre composition (for example, wood free as opposed to up to 70 per cent. groundwood) nor on the type of filler (china clay, talc, or coating clay) except, possibly, in one case, annaline; increasing the total percentage of filler appears to affect the top side layers rather more, while increasing machine speed causes the plateau region of relatively steady filler content to narrow, and the reduction in content as the wire side is approached extends over a greater thickness of the sheet.

These results, together with those from other experiments, led Groen to confirm Hansen's original findings and to conclude that the basic shape of the filler distribution curve is explicable in terms of natural self-filtration through a growing fibre mat. Further, in one direct comparison the substitution of several open-type table rolls for solid rolls had only a slight effect on the distribution curve and this is taken as confirmation that the 'washing-out' effect, which should be greatly reduced in open rolls due to the lower quantity of water adhering to the surface, is not of great significance. Wrist (84) concurs with this view and has stated that the substitution of foils for table rolls, though affecting the overall filler retention, does not alter the distribution within the sheet. In sum then the weight of evidence favours the natural drainage theory though it is only fair to point out that the 'washing' effect of the table rolls still has much support as an explanation and considering the other disturbances which are known to occur in the roll nip it could well be relevant at least in high speed operation.

3A.2 8 Two-sidedness in fibre distribution

All the work referred to so far has concerned loading materials though it has always been considered that differences in smoothness between the two sides of a sheet are due equally to loss of fines from the wire side. Close observation of the two surfaces, as in the light micrographs of Emerton, shows that on the wire side longer fibres are exposed with more gaps and concavities prominent between them, particularly when groundwood and fine fibre fragments are present in quantity in the fresh stuff. Further evidence of the increased fines content of the top side of a sheet is that it has been found to be composed of fibres having a slower freeness (112).

This difference in fibre composition on the two sides is also considered to be one of the causes of colour difference which can be so annoying in fine papers. Hinton (76) has pointed out that surface reflectance differences originating from the differences in smoothness and fibre orientation between the two sides are partly responsible for this, but the main trouble is essentially that various sizes and shapes of fibres and particles of loading are liable to be dyed to a different intensity. Pigment dyestuffs should obviously be avoided to reduce two-sidedness in colour because they behave in a

similar fashion to loadings, but little can be done to alter the fact that soluble dyestuffs have different affinities to loadings and fibres; the intensity of colouring is generally greater for fines than long fibres though it varies with the origin of fines (whether resulting from beating or naturally occurring) and depends on many other factors. If, as is usually the case, the difference in intensity between the dyeing of long fibres and fines presents the more important contrast, then the top side of the sheet will be enriched in colour due to the greater quantity of fines present there; if, however, the dye has a much stronger affinity to fibres than to the filler, this may become the more important effect and it is then possible for the wire side to be enriched due to its lower loading content.

There has not been much work done on how fibre composition varies through the sheet though several investigators have tried adding dyed fines to furnishes and examining the relative quantities appearing in the two sides of the sheet. There has been a general confirmation that fines appear in greater quantities on the top side of paper made on both slow and fast machines. Forgacs and Atack (73) have investigated a special though highly relevant aspect of this subject by determining the proportion of chemical pulp to groundwood present through the thickness of sheets of newsprint; a microtome was used to obtain the sections and the proportion of each pulp was determined by a technique dependent on the differences in lignin content remaining in the fibres after their respective treatments. Several sheets of newsprint made at different machine speeds and with a relatively wide range of average chemical pulp percentage were tested; in all cases the proportion of mechanical pulp was much lower than the average on the extreme wire side, though within the sheet it increased rapidly to reach a maximum and thereafter decreased slowly towards the top side.

This is similar to the distribution of loading through the thickness of a sheet of paper and both may be explained in general terms as follows. At the start of drainage the longer fibres are held in the meshes of the wire while the fines tend to pass through. As the mat builds up the longer fibres act as a sieve of decreasing mesh size, so retaining more fines, and at the same time the lower layers become more compacted. In the upper layers some movement of fines downwards between the longer fibres may occur (thus accounting for the reduction in fines and loading on the top side) until the web becomes so compacted that relatively little movement between the fibres is possible any longer.

3A.2 9 Fibre orientation; general observations

In the vast majority of papers it would be desirable for the various strength and other physical properties to be approximately isotropic, i.e. the same in all directions. In practice strength and rigidity tests taken in the machine and cross directions can differ appreciably and the basic cause of this is a preferential alignment of fibres in the machine direction (see, for example, reference 91). Differences between the machine- and cross-direction stresses

in the sheet, particularly during drying, also introduce anisotropy but this subject will not be considered at this point.

Several methods of assessing fibre orientation based on the highlighting and examination of a small proportion of fibres in the sheet have been used by different investigators, but without exception they are rather tedious to use. Usually in laboratory work a small proportion of fibres are dyed and a silurian effect produced in the finished sheet; for work actually on the paper machine the fibres may be dyed with a fluorescent dye which is visible in ultra-violet light or in certain cases fibres may be mordanted with tannic acid and made visible in the finished sheet by suitable dyeing. Various devices have been designed to aid the process of determining and recording the direction in which individual fibres lie, but in all cases a great many fibres need to be counted to achieve any reasonable accuracy and there are many difficulties, particularly with longer fibres that may twist in several directions. Recent reported methods have generally been adapted from the technique developed by Danielson and Steenberg (35, 45), although Forgacs and Strelis have devised a relatively simpler method based on counting the intersection of fibres with two lines in the machine and cross directions (88). Attempts have been made to instrument this process of counting by using transmitted light through suitably placed slits, but little success has been achieved. A more promising line has been the application of X-ray diffraction techniques to show up any preferential alignment and reasonable correlation with anisotropy of strength measurements has been achieved in this way (33, 41).

In earlier discussions of the flow of individual fibres in the slice jet, evidence has been cited to show that there is a preferential alignment in the machine direction. In the first layers deposited on the wire this preferential orientation may be accentuated as differences in velocity between the jet and the wire produce a drag on the fibres; layers deposited later when the relative motion of stock and wire is practically zero may be expected to retain only the original orientation effect and consequently fibre orientation is generally greater on the wire than the top side, see Fig. 3.5. Shake also has an effect on orientation of the fibres but discussion of this will be left till later.

3A.2 10 Changing fibre orientation on the wire

The manner in which the initial orientation of fibres in the jet stream is affected before they are fixed in the sheet depends on the presence of a relative motion between undrained stock and the existing mat, and can be explained as follows. If the fibre were lying horizontally in the stock on the wire and at one particular table roll settled completely into the mat during drainage, then even if there were a substantial difference in velocity between the stock carrying the fibre and the mat fixed on the wire, there is no reason why the orientation of the deposited fibre should be affected; in this case the initial orientation of the fibre in the slice jet is unaltered and the whole fibre is, as it were, fixed simultaneously into the sheet. But in a jet in which the fibres lie at random in all directions, most will

206

have some vertical component of orientation; subjection to the short, impulsive downward forces produced by suction at the table rolls may then fix one end of the fibre leaving the other relatively free to move in the

MACHINE DIRECTION
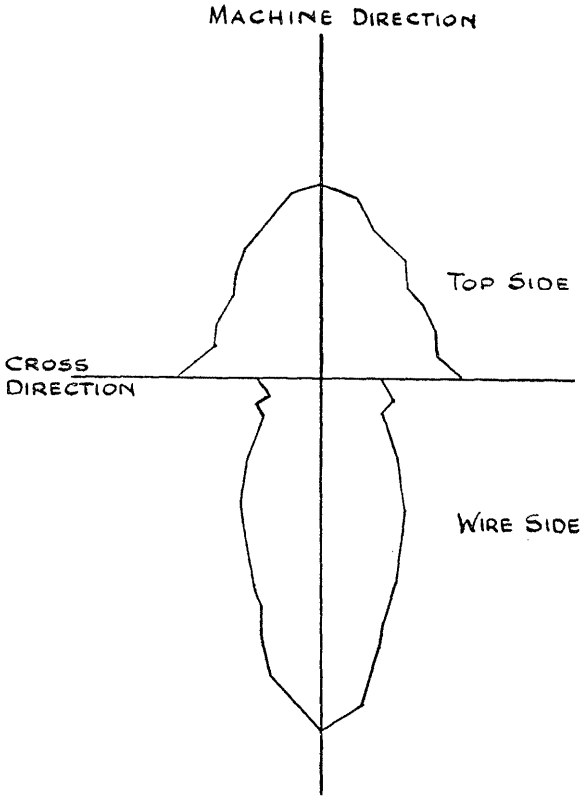
TOP SIDE

CROSS
DIRECTION

WIRE SIDE

Fig. 3.5. Fibre orientation distribution on top and wire sides of paper (after Glynn, Jones and Gallay)

liquid stock. In this situation any relative velocity between the free end of the fibre and the mat will affect the orientation to an extent dependent on the time lapsing before the next roll produces another downward impulse and fixes more or all of the fibre into the mat. In particular, a slice jet meeting the wire at a lower relative speed will accentuate the small existing machine-direction alignment of fibres especially in the slow, narrow boundary layer of the jet which first contacts the wire.

This theory was first developed by Finger and Majewski (11) to explain some observations on the effect of shake. Wrist (84) has since pointed out

that the conception of one end of a fibre being fixed and the other free to move is too simple. In fact the boundary between a fixed and a free portion of a part-vertically aligned fibre must be diffuse, and it is more realistic to consider that one end of the fibre extends down into a zone of higher consistency and stronger fibre-network structure which inhibits movement to a greater extent than in the lower consistency of the upper regions. Change in orientation due to relative motion of wire and stock is thus still possible but the effect must become less pronounced further down the wire as the overall consistency of the mat increases (which is why attempts to apply shake at the dry-end of the wire have met with little success). This, combined with the progressive decay in relative motion between fibre in the liquid stock and the mat beneath as the sheet builds up, explains the reduced fibre orientation in the top side of paper.

It is apparent from this explanation of fibre orientation that natural forming conditions on the wire and the initial orientation of fibres in the slice stock both contribute to alignment in the machine direction; only the influence of shake produces forces which can counteract this tendency, although it is also possible that the small-scale turbulence induced in the stock as the wire passes over a table roll has a randomizing effect which reduces alignment. For these reasons paper made on the Fourdrinier machine inevitably has some degree of machine-direction orientation producing anisotropy; as in the case of two-sidedness, although some alleviation of the differences may be achieved by careful experimentation in the light of the foregoing explanations of the phenomena, it is not realistic to expect that the differences can be eliminated altogether.

3A.2 11 Curl

Because of the differential shrinkage of fibres during drying along and perpendicular to their length, two-sidedness and fibre orientation effects interact to produce the condition known as curl, a phenomenon which is far from easy to explain. This subject will be dealt with more fully in Part 5 and for the moment attention is confined to discussing the influence of formation conditions on curl.

The difference in degree of orientation between top and wire sides, as shown for example in Fig. 3.5, is the basic cause of curl in paper, though the issue is complicated because the average potential shrinkage of the two sides is different (due to differences in composition of the fibres as explained in the previous section) and because of the effects of different drying stresses in the machine and cross direction. Work on this subject particularly by Brecht and his colleagues (44), Glynn and his colleagues (45, 55, 74), and Hendry and Newman (89), though producing some clarification has served to underline the interactions between these various factors which occur in practice, and so far only a general qualitative explanation of the direction and degree of curl exhibited in any particular case is possible.

Briefly, it is important to realize that neither two-sidedness nor fibre orientation on their own would produce curl along a particular axis, both must be present. If the fibres were randomly arranged in the paper but

the usual two-sided composition were present, then in the absence of drying restraints, or of drying taking place more on one side than the other, the sheet would exhibit a general bending inwards in a circular manner towards the side which, by virtue of its composition or density, had contracted most; for example, handsheets dried in air show a tendency to fold inwards towards the wire side because, presumably, the higher density and presence of a greater percentage of fines on the wire side of handsheets gives proportionally more contraction during drying. If, on the other hand, fibre orientation were strong but uniform through the thickness of the sheet and there were no two-sidedness, then on drying without restraint the paper would contract more in a direction perpendicular to the preferred orientation of the fibres, but would remain flat. Only when fibre orientation differs one side of the sheet from the other will the relative shrinkage in machine and cross directions differ also on the two sides, and then the interaction of shrinkage forces will cause the paper to bend along one particular axis (this axis is usually defined as the direction of the line of paper remaining flat on the support surface). This axis appears to be determined largely by the side having stronger fibre orientation; this side has greater shrinkage perpendicular to the direction of orientation which produces a tendency to curl towards that side along an axis parallel to the direction of alignment. In his investigations Glynn found that the difference in the degree of orientation between the wire and top sides bears quite a close linear relation to the degree of curl exhibited by papers dried under similar conditions (45).

Due to the greater machine-direction fibre orientation normally found on the wire side the usual structure of machine-made paper produces on drying a tendency to curl with axis in the machine direction and towards the wire side. It must be emphasized, however, that in practice drying restraints affect this and can even reverse the direction and axis of curl; in addition differential drying or damping, for example in an M.G. paper or when using a sweat roll, can affect curl irrespective of other factors. Finding the solution to any particular curl problem requires study from many aspects, including those of the drying conditions which are described in 5A.3 8 when the subject is dealt with in more detail, but the approach must always be made bearing in mind the fundamental considerations outlined above.

3A.3 DRAINAGE AT THE SUCTION BOXES

The water/fibre ratio of stock on the wire after the last table roll is between 50 and 30, i.e. the consistency, solids content, or dryness of the fibre mat (by definition these are all the same) is roughly from 2 to 3 per cent. After passing over the suction boxes on the average machine the water/fibre ratio is down to between 9 and 5, i.e. the solids content between about 10 and 17 per cent. Bennett (9) estimated that on one machine the suction exerted in the first box was similar to that developed in the last table roll, though the box extracted six times as much water. The value of suction boxes is thus clear and to a great extent their efficiency under given conditions

governs the dryness of the sheet at the couch. It is all the more surprising then that so little has been done to investigate this particular part of the Fourdrinier and until relatively recently there have been only rough ideas current as to how the suction box works and what influences its efficiency.

In passing over a suction box each part of the web is subjected to vacuum for a particular length of time and this (assuming the open length of the box is the same for all points across the wire) should result in a uniform increase in the solids content. One of the fundamental aspects to determine is how the increase in solids content depends on the vacuum, the length of time it is applied, and the initial solids content, i.e. the position of the box. A certain quantity of air is pulled through the sheet into the suction box and up to a point this affects the power used by the vacuum pump. It is therefore important to know at the same time how this volume depends on the three variables so that, if necessary, pumping costs can be related to the increase in solids content. In the discussion following let it be clear at the outset that reference to a higher, greater, or increased vacuum implies a lower absolute pressure, i.e. a greater difference from atmospheric pressure.

3A.3 1 Machine experiments by Brauns and Oskarsson

Brauns and Oskarsson (5) were the first authors to report results relating to the foregoing and their work remains valuable because it was undertaken on an experimental machine rather than, as in most subsequent cases mentioned below, on an apparatus designed to simulate suction box action. All the results were taken on one particular suction box, one section of which comprised a single compartment beneath a normal slotted cover, while another section was divided parallel to the slots into three separate compartments; the vacuum applied to each compartment could be varied and the resulting drainage from the web measured. The solids content at the leading edge of the suction box was approximately 4 per cent. in all cases.

Applying the same vacuum to each of the three successive compartments gave the results shown in Fig. 3.6; in this graph the quantity of water extracted is expressed as a cumulative percentage of the total in the web before passing over the box. It is apparent firstly that the quantity of water removed in each successive compartment reduces and this may be expected because there is less water remaining for removal. If the quantity extracted is expressed as a percentage of that remaining to be removed, however, it may be shown that this also reduces so that the effect of a particular vacuum is less the drier the web. Finally it may be noted that as vacuum is increased it has less effect on the water removed; thus, with a vacuum of 800 mm. H_2O or 2·3 in. Hg almost 50 per cent. of the water initially in the web is extracted, but with a vacuum double this the percentage increases to only about 65 per cent.

From this data two points may be deduced: to remove the same proportion of water at each successive box a higher vacuum is required; and the quantity of water extracted increases as the vacuum is raised, but with

diminishing effect. The second of these points is important when considering the relative value of extracting more water at the suction boxes by means of a generally higher vacuum at the expense of greater power consumption and shortened wire life. The first point leads to the notion of gradually increasing the vacuum applied to successive boxes instead of keeping it uniform, and this formed the second part of the experimental work reported by Brauns and Oskarsson. In this case exactly the same general conditions pertained but instead of applying the same vacuum in each box the first one was reduced by 200 mm. H_2O and the third increased
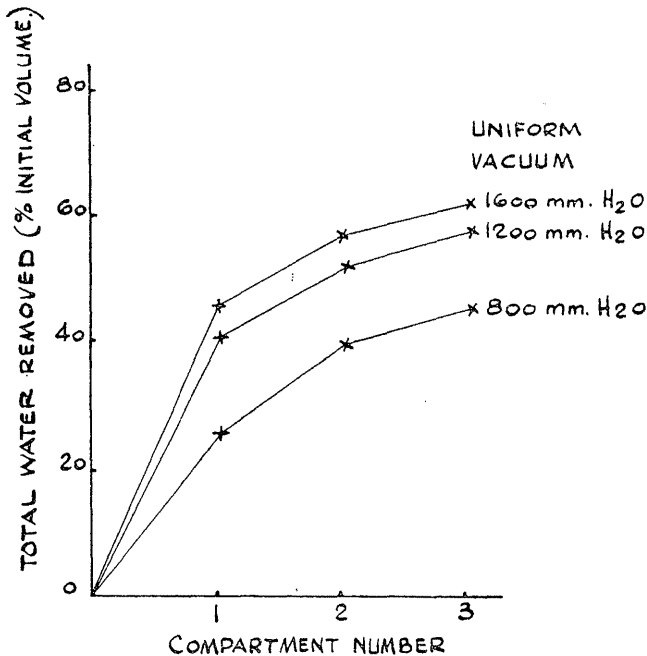
Fig. 3.6. Water removed in successive compartments of a suction box expressed as a percentage of the initial volume of water present in the paper; shown for three different vacua uniform in each box (after Brauns and Oskarsson)

by this amount. The result of this was to increase substantially the quantity of water removed and in Fig. 3.7 the effect on the ultimate solids content of the sheet for different average vacua is shown. To achieve the same solids content without staggering the vacuum applied, a higher uniform vacuum would be required with consequently greater power consumption, lower wire life, and other disadvantages.

Measurements of the volume of air passing through the box compartment were also made and it was estimated that air flow commenced when the sheet was between 6·5 and 7·5 per cent. dry, though this figure will

211

depend essentially on the degree of consolidation of the web and other factors. The results show that under a given vacuum the air flow increases as the sheet becomes drier, but this is not accompanied by a corresponding rate of increase in water removed; Brauns and Oskarsson conclude that the initial quantity of air flowing through is therefore of greater significance and the reason for this will be examined shortly.

3A.3 2 Suction box simulation experiments

Apart from a general confirmation by Tepelnev and Sokolov (30) that staggering the vacuum in the boxes of a paper machine gives an improvement in drainage over uniform vacuum (the average being the same in
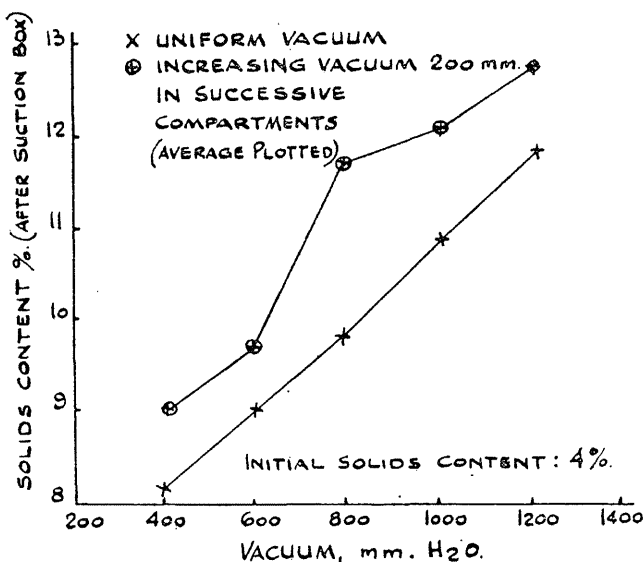
Fig. 3.7. Solids content of web drained at different vacua under uniform vacuum and under progressively increasing vacuum (after Brauns and Oskarsson)

both cases), almost all other experimental work on suction boxes, notably by Nordman (14), Müller-Rid and Pausch (28), and Attwood (53, 40), has been done with apparatus designed to simulate the action of a suction box. The first two workers used a stationary drainage device in which there was no simulation of the scraping action between the wire and box which occurs on the machine; Attwood has shown that this action is highly important so that the value of this earlier work is limited though the general conclusions probably hold good.

Nordman used a constant delivery vacuum pump in his work which meant that the vacuum varied according to the porosity of the sheet; thus,

although he found that adding fines to the stock produced an increase in the dryness after a given suction period, this may well have been the result of a greater vacuum due to the increased density of the sheet. Müller-Rid and Pausch controlled the vacuum and obtained an opposite result, i.e. that free pulps drained easier under given vacuum conditions, and also a greater volume of air passed through the sheet; this accords with common observations that when stock on the wire becomes free either the vacuum falls or, if it is regulated, the air flow from the boxes increases. These workers also confirmed that the vacuum is the most important single variable affecting the drainage rate and under given conditions there appeared to be a substance of sheet at which the final solids content was highest; the value of this optimum substance increased at higher vacua and with greater beating of the stock.

Apart from these results the work of Müller-Rid and Pausch is interesting in showing the effect of continual application of a steady vacuum. Fig. 3.8a shows some representative curves and it will be noted that prolonging application of vacuum has a steadily diminishing effect on the ultimate solids content of the sheet. This is particularly noticeable for lower vacua, when it may also be observed that the curve flattens off earlier even though the quantity of air passing through the sheet steadily rises, as shown in Fig. 3.8b. The implication of this is that the lower the vacuum at a box, the less time it should be applied, because a point is soon reached where little further dryness is achieved despite the fact that air drawn through the sheet, and consequently the pump power consumption, continues to increase. Under any particular machine conditions it cannot be easy to find whether the total time of application of suction to the sheet represents a good compromise between producing a sufficiently dry sheet and using excessive power (both as a result of drawing through too much air and having a larger friction area on wider boxes). It may be suspected that, especially on slow machines, it is common to have an excess of suction area; indeed one worker, Shamolin (61), has reported a considerable power saving with negligible decrease in solids content of the web resulting from reduction of the width of suction boxes to a third.

Certainly, it is worth experimenting with the available suction area on a machine and it is quite possible to find that one or two boxes at the dry end can be lowered, and the overall vacuum on the remaining boxes raised slightly to compensate, but the effect is to decrease the total power consumption and increase the life of the wire.

3A.3 3 Attwood's experimental work

B. W. Attwood (53, 70) began his investigations into the action of suction boxes by designing a laboratory simulation apparatus similar in basic principles to that of Müller-Rid and Pausch. However, it soon became apparent that the apparatus, though producing similar results to those obtained by Müller-Rid and Pausch, in fact removed far less water under the same vacuum conditions than occurred on a Fourdrinier machine when using the same sort of pulp. Various differences in the characteristics
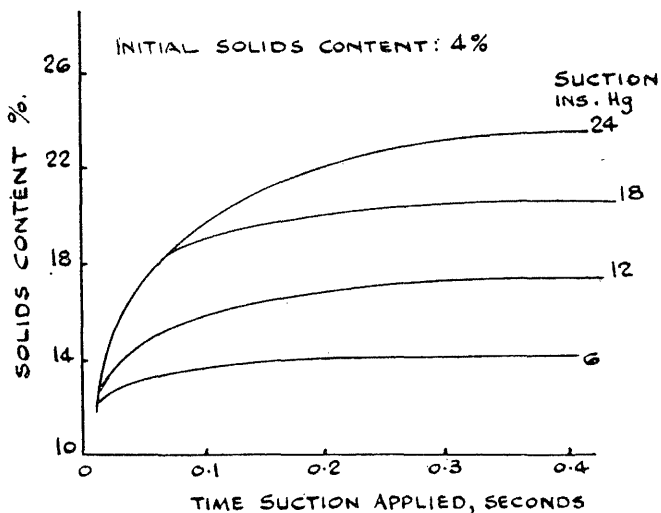
Fig. 3.8a. Final solids content of sheet after application for varying time period of different vacua (after Müller-Rid and Pausch)
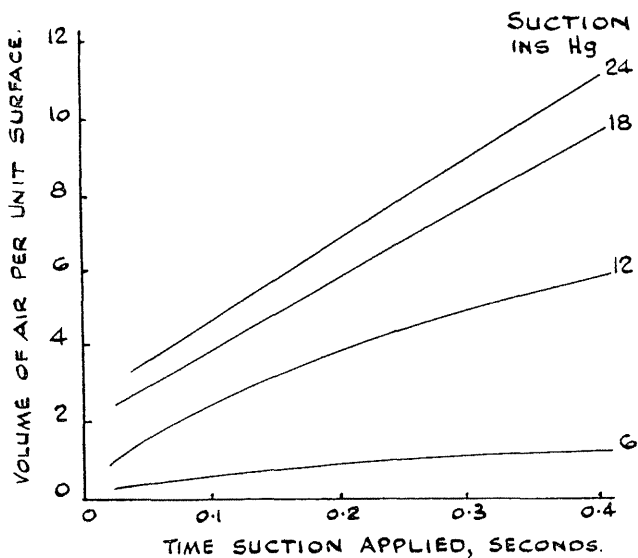

Fig. 3.8b. Volume of air passing through sheet after application for varying time period of different vacua (after Müller-Rid and Pausch)

214

of formation of the sheet on the machine and in the laboratory apparatus were ruled out as possible explanations of the discrepancy, and it was decided that the scraping action of the wire on the suction boxes must have an important effect.

Observation with a high-speed ciné camera of the underside of the wire on the laboratory apparatus and (by fitting a simple slotted suction box with transparent plastic sides) on a pilot Fourdrinier machine confirmed the difference in action occurring in the two cases. With the static laboratory apparatus, during the vacuum period water is disengaged from the wire as drops and spray from bursting bubbles but a substantial quantity of water remains attached to the underside of the wire by surface tension forces. This water, particularly at higher solids content, is rapidly sucked back into the sheet in a matter of a few hundredths of a second after the
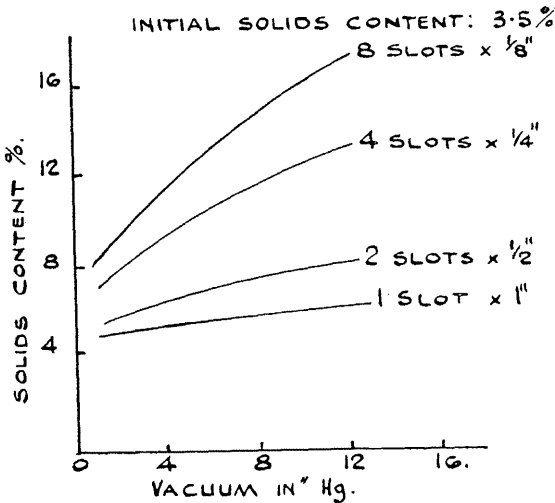

Fig. 3.9. Relation between solids content and vacuum applied to different widths of slots, the suction width totalling one inch in each case (after Attwood)

vacuum is shut off and this is attributed by Attwood to elastic expansion of the layer of fibre next to the wire; under vacuum this layer is compacted by the difference in pressure and on release of the vacuum water is pulled from the underneath of the wire and from the mesh of the wire to fill the intersticial volume created between fibres. On the Fourdrinier the water pulled underneath the wire by the influence of vacuum could clearly be seen being removed in considerable quantities by the scraping action of the trailing edge of the suction box slot.

Accordingly, a new laboratory simulation apparatus was built comprising a shallow container with a wire mesh bottom placed above a vacuum chamber; the wire and vacuum chamber are separated by the outer part of

a large solid circular disc into which slots or other shapes of hole can be cut at intervals. When the disc is set in motion revolving about its centre the effect is to reproduce the dynamic conditions of drainage on a paper machine with the only difference that the suction box slots move relative to the wire instead of vice versa. This apparatus proved to simulate conditions of drainage on the machine wire very closely.

Observations by Attwood with this modified laboratory simulation apparatus showed that increased temperature and reduced consistency both produced better dewatering. The importance of the scraping action was confirmed by determining the solids content achieved using numbers of different width slots adding together in each case to the same total length; thus, in Fig. 3.9 the resulting solids content from using $8 \times \frac{1}{8}$ in. slots, $4 \times \frac{1}{4}$ in., $2 \times \frac{1}{2}$ in., and 1×1 in. slot can be compared for different vacua (initial solids content was 3·5 per cent.). It is apparent that the more slots are used, i.e. the more the vacuum area is subdivided into slots of smaller width, the more effective is the application of vacuum (there will, of course, be a lower limit to this effect, as discussed below). Looked at another way, if for any particular slot the width is extended beyond a certain point, the vacuum will cease to have any further significant effect and it would be more beneficial to use up the available area by starting another slot; this, therefore, confirms the conclusion reached earlier by Müller-Rid and Pausch when they compared the effect of applying vacuum for varying lengths of time.

Attwood also determined from his results that it is possible to reach only a certain maximum solids content in a reasonable time with a given vacuum, and to increase the solids content above this value requires a higher vacuum. This again confirms the same result obtained by Müller-Rid and Pausch. The advantages of increasing the vacuum as the web gets drier, compared to using the same average uniform vacuum on all boxes, was also demonstrated. Increased speed had the effect of reducing the dewatering capacity with a given vacuum, as did increase in substance of the sheet (contrary to the findings of Müller-Rid and Pausch with their static simulation apparatus).

3A.3 4 Summary of suction-box operation

From the foregoing it is possible to give a reasonably consistent explanation of the course of water removal at the suction boxes and to some extent to deduce how present suction box arrangements may be operated or modified to improve their performance.

At the first few suction boxes the increased pressure differential acting on the two sides of the sheet causes compression, and water is squeezed out through the capillaries in the web; due to the elastic condition of the mat the compression must initially occur mainly in the lower layers of the sheet where the change in pressure is first felt. Some water sprays through the wire into the suction box, but probably the majority is removed at the trailing edges of the slots or holes of the box where it is scraped off from underneath the wire. No air is sucked through the sheet at this point.

On release of vacuum the web expands and very rapidly draws any water in the wire mesh or remaining underneath the wire back into the web.

As the web gets progressively drier water must be removed from smaller capillaries, requiring a greater differential pressure. Thus, it is to be expected that the higher the temperature of the water, and hence the lower the surface tension and capillary resistance, the easier it should be to dewater the sheet. In this phase, when the web is becoming relatively less saturated, the compressibility and elasticity of the fibre mat will also presumably be of importance.

The point is soon reached when the upper layers of fibres in the sheet are freed of their overall film of water (visible as the dry-line) and air enters the larger capillaries. Each release of vacuum will then cause some water to migrate upwards back into these capillaries, but as soon as vacuum is re-applied they will be cleared, together with more capillaries in the lower layers, until eventually continuous air channels are formed through the sheet (this occurs at 6·5 to 7·5 per cent. solids content according to Brauns and Oskarrson). A small quantity of air passing into the suction box is probably of some benefit in assisting the transportation of water particles, but it is almost certain that evaporation from the web due to passage of air through it is of no particular significance. Fibres which have been more heavily beaten will generally compress easier and form a smaller average capillary size, so that removal of water from the web will require greater suction to achieve the same dryness while less air will be sucked through the sheet.

Together with this general explanation the following points drawn from the experimental results mentioned earlier are worth reiterating:

(a) A higher vacuum is required to remove the same proportion of water when the sheet is drier.

(b) At any particular dryness of the web, increasing the vacuum increases the quantity of water removed, but with diminishing effect.

(c) There is no value derived from applying vacuum beyond a certain (relatively short) length of time because this only raises the quantity of air drawn through the sheet for little increase in solids content; also the lower the vacuum applied the less time is needed to reach the optimum point.

(d) The scraping action of the trailing edges of suction box slots provides a highly important contribution to the removal of water and, up to a point, the greater the number of scraping edges, i.e. the narrower the slots, the better.

From these observations the following conclusions may be justifiably drawn:

(a) In the first two or three boxes the vacuum applied need only be relatively small (sufficient to ensure an adequate film of water under the wire) but should be progressively increased.

(b) The vacuum applied to the sheet when it is becoming relatively dry, and particularly once air is being drawn through the sheet, still

needs to be progressively higher to have an adequate effect on the sheet, but a limit must probably be reached in the last two or three boxes above which little additional benefit is derived from continuing to increase the vacuum to too high a value.

(c) As a consequence of (a) and (b) probably the best arrangement of applying vacuum in the suction boxes is to have a progressive increase (of perhaps $\frac{1}{2}$ in. to 1 in. Hg.) up to the last two or three boxes beyond the dry-line which then remain at a normal running maximum.

(d) With the qualification that the proportion of surface area of a box to the vacuum applied has an influence on the drag exerted on the wire (see **3B**.41), the gap between different boxes and between slots and holes in a box should be as narrow as possible to avoid reabsorption; this point applies especially to the drier boxes but may be expected to be of significance mainly on slower machines.

(e) A compromise must be reached in the machine-direction length of each slot or hole between subjecting the web to vacuum for a sufficient enough time for it to have effect, and providing as many scraping edges as possible; for the first two or three boxes a further consideration may be to ensure the slot is wide enough to conduct the water away adequately.

(f) The width of slots at present in common use may generally be too wide (Attwood assessed that there is little advantage in having slots greater than $\frac{1}{2}$ in. width; however, his results in this respect, though admittedly showing no dependence on speed, were for machine speeds equivalent to under 400 feet per minute and are not necessarily capable of extrapolation to higher speeds).

(g) Combining (d), (e) and (f) it seems reasonable to suggest that the first two or three boxes should be equipped with the usual cross-direction slots, narrowed to about $\frac{1}{2}$ in. in width and possibly with edges angled in the direction of flow to help scrape off the water under the wire and conduct it away (though this presents a design problem because, unless the whole box is constructed with each slot falling away at an angle (see for example reference 101), account has to be taken of the surface gradually wearing thus causing the land area to diminish and necessitating replacement after a smaller depth than usual has been worn away); also the gap between individual slots should be as narrow as possible compatible with adequate structural rigidity of the box.

(h) Towards the drier boxes it is desirable to lengthen the time of application of vacuum. Since the vacuum itself is greater in these boxes a point must be reached in widening the slot design where wear on the wire is accentuated by the tendency of the wire to dip into the slots; thus, drier boxes are probably better equipped with the staggered hole pattern, though the individual holes could perhaps usefully be elongated in the machine-direction to 2 in to 3 in in length provided their arrangement still permits each part across the web to be equally treated. As an alternative to this one or other of the herring-bone designs should achieve roughly the same effect.

3A.4 CONDITIONS FOR COUCHING

In this section it is proposed to give only some brief details relating to general conditions of couching the web from the paper machine wire; the various methods by which couching takes place and the sheet is carried over to the presses will be given individual treatment later. The open draw commonly used on all but the faster machines is intimately associated with the general problem of couching, so this will also be considered here.

3A.4 1 Forces governing couching

The effort required to pull the web from a paper machine wire is governed by the relation between two primary forces: the adhesive strength of the web to the wire, and the effectiveness of tension in the web in overcoming this adhesion. This relation has been found to depend closely on the angle at which the sheet is pulled off, not simply because the effective pull vertical to the wire obviously reduces as the angle becomes more acute to the wire, but also because the adhesive resistance itself varies with the angle. For the moment this aspect will be ignored and attention confined to discussing what affects the adhesion of web to wire irrespective of the manner in which the web is stripped off.

In fact, little work has been done on this subject though it is considered likely that several factors can increase the adhesion of web to wire at the couch, in particular coarser mesh wires and the greater fibre entanglement in the wire which would be expected to occur under conditions of early, rapid drainage or heavy suction on the boxes. Also the material and weave of the wire is likely to affect the adhesion (it has been suggested that plastic wires give less adhesion than metal) and the composition and degree of beating of the furnish.

In practice, however, the most important factor affecting adhesion at the couch appears to be the presence of a film of water on the underside of the mat. This may be thought of as providing a loosening of the fibre layer in immediate contact with the wire by reducing the strong surface tension forces binding individual fibres into contact with the wire strands. All methods of couching depend for their effectiveness on the provision of such a film of water on the underside of the sheet. With the jacketed top couch above a solid wire couch roll the pressure exerted on the wet web serves to produce this film; with a suction couch the same effect is achieved by the pressure differential resulting from the suction pull. In both cases, of course, an important effect of the couching arrangement is the increase produced in the solids content of the web, though this is really a separate, and subsiduary, function from the actual operation of couching.

If the film of water, once produced, remained between the web and the wire, then designing a couching arrangement would be relatively easy. In practice the water is sucked back into the web as pressure on the sheet is released in a manner identical to that occurring with suction box operation, as discussed above. Moreover, at the solids content met with at the couch this reabsorption occurs extremely rapidly; Baggallay (17) and Hen-

219

dry (19) in their investigations of suction couch shadow-marking (see next section) have both given examples of this. The first author quotes an increase in water/fibre ratio to 6·9 from 5·2 on one machine, and 5·7 from 4·9 on another, obtained by running a slack instead of a tight draw and thereby leaving the web in contact with the wire a few inches further round a suction couch roll.

Baggallay and Hendry also point out that the web can be pulled off the wire immediately after the final suction box with little trouble, but further down the wire this becomes more difficult and fibre is likely to be left adhering to the wire. Baggallay also showed that, irrespective of the solids content of the web, a simple suction box placed under the wire at the point of couching considerably reduces the tension needed to pull off the sheet. Originally in couching from a position between a suction couch and forward drive roll on one machine, adhesion of the sheet was so high that an appreciable fibre pattern was left on the wire and the tension required to effect couching was considerable; applying the suction box removed this completely and allowed a much slacker draw. These observations again demonstrate the importance of a film of water between sheet and wire for reducing the adhesion.

3A.4 2 Shadow-marking at a suction couch

It is appropriate at this point to deal with the question of shadow-marking caused by a suction couch; this subject was the original reason for the investigations of Baggallay and Hendry mentioned above and what follows is largely drawn from their reports. If the web is pulled off the wire close to the trailing seal-strip of a suction couch then a pattern can be observed in the paper, either by eye on slow machines or with the aid of high-speed photography or a stroboscope on faster machines. This pattern shows up in the form of darker areas which correspond to the holes in the suction couch, and it has been proved that the sheet in fact comes away wetter over the hole regions under these conditions. The pattern usually remains visible in the paper at the reel-up due most likely to a difference in bonding of the fibres at the presses that produces an optical effect in the finished paper. This particular effect is described in more detail when considering shadow-marking at a suction press in 4A.2 4.

The difference in water content in the two regions is attributed to the fact that immediately the vacuum is released the web absorbs water from the wire opposite the holes due to the sudden change in pressure differential and up-rush of air, while over the land areas surface tension forces on the couch shell hold water more strongly in the wire and prevent reabsorption by the web to the same degree. If couching takes place closely after the trailing seal-strip terminates the wire is observed to be dry opposite the holes and wet opposite the land areas, which confirms this explanation. It might be expected that the suction force in the holes would have the opposite effect, i.e. tend to remove more water from the web opposite the hole areas so making them drier. This does not appear to occur to any significant extent and it must be presumed that water drawn into the suction

couch holes comes fairly evenly from the web while at the same time the wire itself is evenly flooded. When a presser roll is used, however, a slightly greater pressure may occur opposite the land areas of the couch which would produce a lateral movement of water towards the hole regions, thus enhancing the eventual difference in water content.

If, instead of being drawn off the wire close to the suction box seal-strip, the sheet is allowed to remain on the wire for a short distance round the suction roll, then the pattern is observed to fade. This is due to the fact that a greater reabsorption of water by the web occurs opposite the land areas where the wire carries more water, thereby tending to equalize the water content of the web. Redistribution of water laterally within the sheet cannot explain this as shadow-marking when present after couching shows no similar signs of fading in the sheet before reaching the presses.

There is, therefore, a choice between couching the web from a suction couch roll close to the trailing seal-strip, when shadow-marking is likely to be prominent but the average water/fibre ratio of the sheet is low, or alternatively the sheet may be allowed to wrap round the roll a bit further in which case the shadow-marking decreases but the water/fibre ratio increases. In practice the most sensible approach with a straightforward suction couch and open draw arrangement seems to be to draw off the couch at a point where shadow-marking is just within tolerable limits.

3A.4 3 Angle of draw from the wire

With increasing machine speeds the frequency of breaks occurring at the couch when an open draw is used invariably rises, and this can either make faster running economically unsound or necessitate a more costly furnish or greater treatment of the pulp to make the web stronger at the couch. The greater likelihood of breaking is caused principally by two conditions which affect the wet web increasingly at higher speeds. Firstly, a higher tension becomes necessary at the draw to overcome the greater inertia of the web and also to provide the extra effort which is known to be required to effect separation from the wire at higher speeds. Secondly, on any particular machine higher speeds make it more difficult to effect a compromise between having the breast box consistency sufficiently dilute to form the sheet and having adequate drainage in the wire section without excessive vacuum on the suction boxes; the usual result is that the solids content at the couch drops and with it the wet strength of the web.

It is difficult to assess the relative importance of either of these factors; the first will increase in importance with the substance of the paper and the second depends on how sensitive the wet web strength is to alteration in solids content. Lyne and Gallay (13) and Robertson (94) have demonstrated that in the region of 20 per cent. to 30 per cent. solids content, which is approximately that found at the couch on most machines, the change with dryness of wet web strength (tensile breaking length) may be considerably less compared to that at both higher and lower solids content, though some decrease in strength with lower solids content always does occur, see Fig. 3.10; this phenomenon is attributed to a change
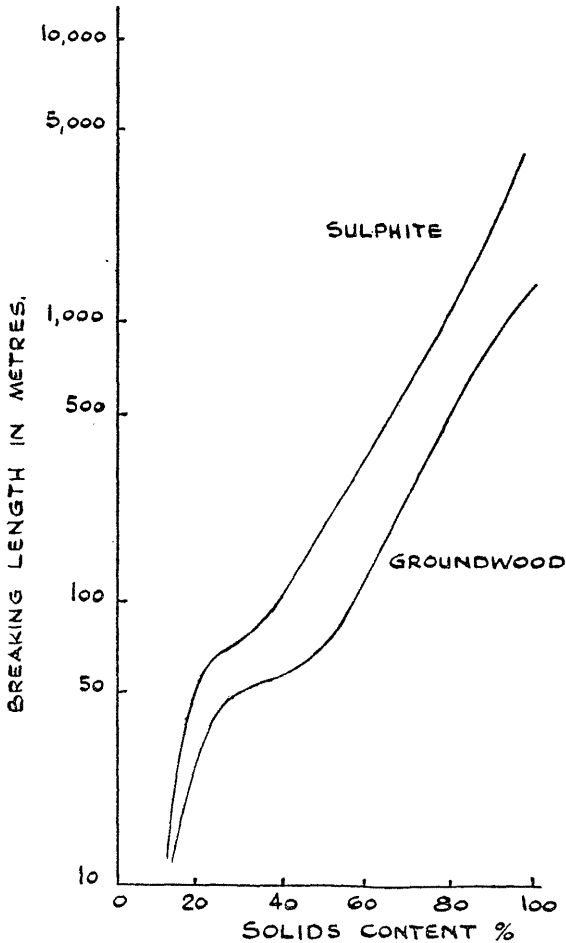
Fig. 3.10. Change in breaking length of sulphite and groundwood wet web with increasing solids content (after Lyne and Gallay)

occurring from surface tension to fibre bonding forces as the main source of cohesion in the web.

Apart from these factors it is apparent that the strain on the sheet at an open draw is very dependent on the draw applied, i.e. on the difference in speed between the first press and the wire. A relatively large difference in speed produces a greater tension, giving a tight draw with the sheet peeling off the wire at an acute angle; a small difference in speed produces less tension, giving a slack draw with a larger angle of take-off. In practice

the machineman uses his experience to set the draw in a suitable position. If he runs the draw too tight the higher tension increases strain on the relatively weak and plastic sheet and so the web is more likely to break either at the couch or further down the machine; at the same time the web width will shrink more and a greater anisotropy of strength and stretch characteristics of the finished paper in the machine and cross directions may be produced. Running with the draw too slack on the other hand
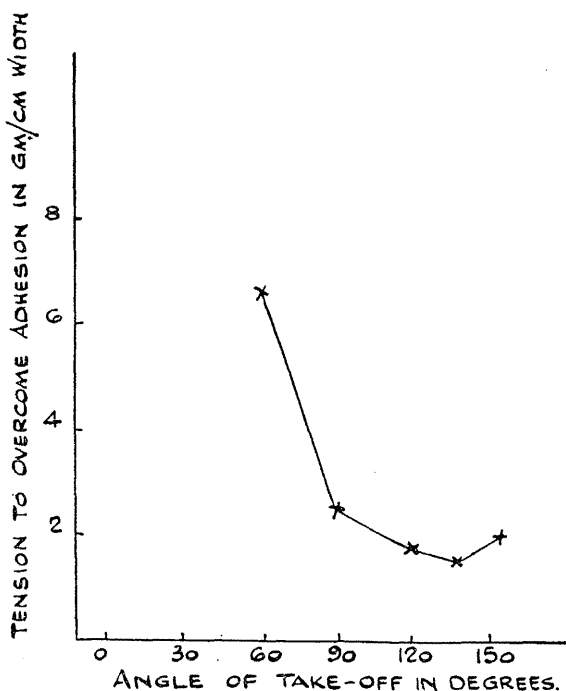

Fig. 3.11. Relation between tension necessary in web to overcome adhesion to a twill wire and angle at which web is drawn off (after Radvan and O'Blenes)

makes the sheet liable to run into longitudinal creases and wrinkles, especially at the edges, and these may be cut through in the calenders.

At first sight it would be thought that maximum effect is achieved if the sheet is couched off the wire at an angle of 90 deg., since in this position the tension has the greatest pull normal to the wire; in other words, if at any time the adhesive force were too great for the tension applied in this direction then the sheet must carry round the couch roll and eventually break. This would be correct if the force required to overcome adhesion were independent of the angle at which the sheet is pulled off, but in fact this is not the case. Several workers have investigated this question both experimentally and theoretically, notably Gavelin (34), Mardon and his

colleagues (37, 59), Howe (46), Radvan and his colleagues (51, 80), Campbell (64), and Osterberg (79). There seems to be general agreement that the effort required to overcome adhesion is closely dependent on the angle of separation and the actual tension needed in the sheet to accomplish couching is at a minimum for an angle greater than 90 deg., usually in the region of 120 deg. to 130 deg., see Fig. 3.11. The implication of this is that under given conditions least strain is put on the sheet if it is drawn off the wire backwards at this angle.

Normally the machineman tends to set draws relatively tightly. This is probably because the creasing likely to come from slack draws is readily observable and to be avoided, whereas to a large extent frequent breaking is not immediately associated with undue strain in the sheet resulting from a tight draw. This is especially the case if the breaks occur further down the machine when any weakness induced in the sheet at the couch is subjected to greater strain; when this occurs the reason for such breaks may be sought more readily in the formation of the sheet or preparation of the stock and the true cause is not always easy to trace. Radvan, in particular, has reported how the frequency of breaks on a paper machine at the open-draw from a press (where a similar situation to that at the couch prevails) steadily decreased as the draw was gradually slackened back from an angle of take-off of about 40 deg. up to 70 deg.; other experiments also showed that running the machine became easier at larger angles of take-off.

How slack the draw may be run in practice depends essentially on the stability of the machine, in particular of the drive and uniformity of the paper. If the angle of take-off from the wire is relatively acute then any increase in adhesion is compensated for by the web remaining on the wire until a larger angle of take-off is reached where there becomes sufficient normal pull to provide the necessary extra force; in other words the operation is stable and self-correcting for any variation in adhesion. If on the other hand the draw were run with the angle of take-off from the wire very close to the minimum tension point, then any increase in adhesion of the web is liable to cause the angle of take-off to exceed the position where the tension has most effect; beyond this point the effective force pulling the web from the wire decreases and a break is certain. In addition, as the angle of take-off is increased flutter of the separation line grows due to the greater change in angle necessary to overcome a given increase in adhesion (this is reflected in the decreasing slope of Fig. 3.11 at higher angles of take-off); this in itself is likely to create stresses which weaken the sheet. Because of the unknown influence of these various factors it is hardly practicable to predict that a machine should run best at some particular angle of take-off and over a long period the point where the frequency of breaks is a minimum can only be found by trial and error. Possibly on most machines once the operating conditions have settled down fair compromise will be found with the draw slackened back to give an angle of take-off approaching 90 deg. In this respect it is important to realise that any relatively large change of draw during normal running may have an effect on the substance. Elongation in the machine direction caused by tension at any draw, but especially at the couch, is not accompanied by

a corresponding shrinkage in the cross-direction; the net effect of increased tension is therefore to increase the area of the paper giving the effect of a reduced substance.

3A.44 Breaks at the couch

Apart from the question of the overall stability of the machine being an essential factor governing the slackness with which the couch draw can be run, in practice the presence of local variations in adhesion of the web to the wire is probably equally if not more important. At any open draw it is possible to see indentations in the line of take-off which may be permanent, intermittent in one position, or simply occurring spasmodically across the sheet. These show up the difference in adhesion caused by such factors as uneven substance streaks, worn or dirty wire patches, plugged couch holes, clogged dandy, and in particular fibre clumps and contraries in the sheet.

Some interesting experiments have been reported by Radvan and his colleagues (51, 80), and by Mardon and his colleagues (59) involving an examination of what happens when the local adhesion at some part of the web becomes too great and causes a break. At normal angles of take-off if a small spot sticks to the couch or a press roll it initiates two tears which run outward on either side of the spot to the edge of the sheet to produce a break. If the angle of take-off is increased by slackening the draw then the tears separate outward more slowly and a point is finally reached at an angle of take-off greater than 90 deg., i.e. when couching the web off backwards, where the tears do not separate at all but run together. In this case no break occurs (at least not immediately) and instead only a small hole is pulled out of the web. Although this situation does not appear to occur on all machines, the rate of separation of the tears always becomes slower at greater angles of take-off and the phenomenon has been observed on both slow and fast machines.

Other observations have shown that a sticky spot having greater adhesion than the rest of the web may not actually start any tears but instead appears to be plucked out of the web leaving only a thin spot in an otherwise intact sheet. This has been termed 'skinning' and has been found to occur more frequently at higher angles of take-off. A break is, of course, less likely to be caused by skinning, so this provides a further reason apart from the reduced tension needed in the web for running at higher take-off angles.

CHAPTER 3B

OPERATING FACTORS AFFECTING THE WIRE SECTION

3B.1 EARLY DRAINAGE CONDITIONS

The conditions prevailing when the stock meets the wire and drainage first takes place are highly critical for the structure and formation of paper. Unfortunately, generalizations on this subject, except for more obvious remarks, are particularly difficult to make since practice in the industry varies appreciably not only between slow and fast machines but also between practically similar machines making the same quality of paper.

Once reasonable running positions for the apron, slice jet, breast roll, forming board, etc. have been determined over a period by intelligent manipulation, the papermaker is generally most reluctant to make any alteration. And not surprisingly so, for interaction of the numerous variables in this part of the process makes it impossible to predict the outcome except in the vaguest of terms; in addition a workable arrangement has to be found for any machine which suits all the grades manufactured without the need for a lengthy engineering alteration each time there is a major change and this, by and large, is a purely empirical process. Even for those machines making the same grade day in, day out, adjustments such as those of the slice lips relative to the wire and to themselves, of the forming board angle, breast roll discharge, slice jet to wire velocity, and many other variables need to be very gradual in nature and carefully evaluated over a long period of time. For this type of investigation a very convenient approach is to use an Evolutionary Operation type of experiment; this is eminently suited to seeking over a long period, and without affecting production, an optimum position of a number of variables which may interact with one another and which affect test properties of the end-product in different ways.

Despite these qualifications to the value of any detailed discussion of this subject, there are several observations which have been reported in the literature that are well worth noting. Most of these concern avoidance of undue disturbances during early drainage of the web on faster machines, though one or two remarks will also be made on how the formation of the sheet (in the general sense of the term) is affected, especially with regard to variation of the stock or slice jet velocity relative to the wire speed. For slow machine operation the most important variable in this field is that of shake but this topic is not considered until 3B.3.

3B.1 1 Impact of stock on the wire

The point where the stock first contacts the wire and the angle of the impact are both highly important from the point of view of formation and the prevention of defects in appearance caused by stock jump and other

226

disturbances. There are generally two conflicting interests in the early part of the wire section which have a close bearing on where impact of the stock occurs: the necessity for drainage to commence as soon as possible in order ultimately to increase the solids content at the couch, and the requirement that this process of dewatering does not disturb or spoil the general formation.

On most machines a compromise is usually necessary on the one hand to avoid excessively rapid drainage in the first few feet of wire length which is liable to disrupt the whole structure of the sheet, and on the other to avoid delaying drainage to such an extent that the sheet leaves the couch very wet and the breast box consistency has to be raised to offset this, while in addition the formation may be spoilt on the top side of the sheet by the results of flocculation. On faster machines an added disadvantage of early rapid drainage can be a prominent wire mark. According to Forgacs and Atack (73), this is due to short fibres being drawn end-on into the wire meshes, wedged there between the predominant longer fibres (which are more likely to span across the meshes), then flattened out in pressing and calendering to form tiny mounds; the mark will, of course, be greater with coarse wires and furnishes composed of a large proportion of fines. Laboratory investigations reported by Dushnicki (110) also confirm that early drainage rate is the key factor affecting wire mark. This will be strong in conditions where the slice jet meets the wire with a high vertical velocity component and early drainage at the breast and succeeding table rolls is rapid. Later stages of drainage at the suction boxes and couch can also affect wire mark but only if the initial drainage conditions are not severe. If, on the other hand, early drainage is very slow and in addition the consistency of the stock is low, then flow over the early part of the wire becomes unstable and oscillating streams emanating from small discrepancies in the slice jet appear on the surface ('skating') and produce variable cross-web substance fluctuations.

The effective total suction in the nip of the large breast roll is considerably greater than for a table roll revolving at the same speed, so if a machine wire is short of drainage capacity it is usual to arrange for stock to contact the wire close to top dead centre of the breast roll. This produces a considerable discharge but nonetheless appears in most cases to give a satisfactory sheet, possibly because the alternative of running without breast roll discharge may necessitate an increase in breast box consistency which destroys any potential benefit to the formation. When running in this way, however, it is very important to ensure that the point of impact of the stock is always close to the top dead centre; if the stock meets the wire beyond this point on the breast roll, allowing a partial discharge, variations in the drainage can occur as the head in the breast box and hence the stock speed fluctuates, or if the wire tension and hence the angle of wrap round the breast roll alters. In practice trouble from these causes is more likely to be noticed in cross-web variations and any misalignment of the breast roll and slice will readily produce a variation across the sheet.

On slow apron machines it is not generally advisable to have the apron terminate over the top of the breast roll, particularly if there is the possibility

227

of a flow down the back of the roll, and in any case drainage on such a machine will generally be more by gravity through the wire. Usually it is more important on such a machine to delay drainage sufficiently for the shake to have the opportunity to influence the mat; for this reason the apron usually extends down the wire short of reaching a position where trouble may be incurred from water under the apron running into channels since this can disturb the mat and mark the wire side of the paper. A better alternative to an excessively long apron would be to use a forming board.

3B.1 2 Reducing disturbances on fast machines

On fast machines the suction exerted at the breast roll becomes considerable and, except for tissue machines with specially designed pressure formation breast boxes where suction may be applied in the breast roll, there are strong arguments against having any breast roll discharge. For one thing the dangers of operating with variable drainage are greater but perhaps the main reason is that stock jump and other disturbances are much more severe at a breast roll.

Mardon and Truman (50), amongst others, have made some interesting observations and a theoretical analysis of the forces operating at the point of impact of a slice jet which are highly relevant to this problem. When the jet meets the wire a certain vertical velocity component is inevitable and this produces a condition in which the upper surface of the jet may become more disturbed on impact by destruction of this velocity. Any small ridge in the jet produced by an imperfection in the slice flow meets the wire with a slightly heavier impact and this may cause the ridge to split or become accentuated. In the worst cases spouts form on the surface of the stock which break away to produce the spray familiar on all fast machines.

With a breast roll discharge the additional downward acceleration induced by the roll, coupled with an upward impulse at the point where the wire wrap round the roll terminates, makes these disturbances more likely to occur and for this reason it is more satisfactory to avoid this method of operation. Higher wire tension, by reducing the wrap round the breast roll, improves the situation, but as the breast roll is unfortunately at the opposite end to the driving roll the wire tension there is comparatively low. Disturbances can also be reduced by grooving the breast roll. Other workers, including Müller-Rid and Pausch (28), have confirmed that less disturbance occurs when there is no breast roll discharge, and it may also be noted that suction of air between the underside of the jet and the wire, which can be very troublesome and affect the trajectory of the jet unevenly and spasmodically, is more likely to occur when the jet meets the wire over the top of the breast roll.

It is equally evident for the same reasons that the stock should meet the wire with as little vertical component as possible; when an apron is not used this requires that the jet leaves the slice near horizontally (setting the slice lips to achieve this condition has already been discussed), and meets the wire in as short a distance as possible (which is also advantageous for reducing the growth of instabilities in the jet). Plainly when no breast roll discharge is desired an engineering problem arises here because a short

jet length with impact beyond the breast roll can only be achieved with the lower slice lip extending well over the roll; to make this sufficiently rigid with adequate clearance above the wire will necessarily increase the vertical drop of the jet, and hence the vertical velocity of impact. In practice a compromise position, in which the jet impinges on the wire close after top dead centre on the trailing side of the breast roll, is often used. In this case the disadvantages possible due to variable discharge have to be faced.

With the slice jet meeting the wire after the breast roll less disruption of the sheet occurs at the point of impact but substantially the same difficulties with stock jump and other disturbances may arise as soon as the mat passes over the first table roll where the first drainage impulse occurs. Grooved rolls and dandy-type rolls have been designed to help overcome this problem and these are discussed in 3B.2 3, but for the moment attention will be turned to the use of forming boards as these are more intimately connected with the conditions of early drainage.

3B.1 3 Forming boards

Forming boards have become increasingly common on fast machines and in their usual position between the breast roll and the first table or grooved roll are thought to serve two main purposes. First, and most important, they reduce drainage in the first few feet of wire length and thereby make the process of deposition of the wire side fibre layer more gentle, and certainly less subject to disturbances than at the breast roll or a table roll. Secondly, their construction enables them to be set closer to the breast roll than a table roll and this has the advantage on wider and faster machines with large diameter breast rolls of reducing the gap between supports, which in turn reduces the angle of wrap of the wire round the breast roll.

Forming boards come in many designs and lengths depending on the papermaker's conception of their function on a particular machine. Some are completely solid but generally slots are cut out at intervals of 2 in. to 3 in. allowing some drainage to take place; occasionally a light suction and drop leg may be applied to these slots. The leading edge of the boards are normally pointed at an angle not greater than 30° to give a smooth cut-off of water carried on the underside of the wire. On fast machines there may be a long series of forming boards interspersed with grooved rolls and foils (see 3B.2 3), the object being to de-water the rolls gradually, but sufficiently to reduce stock jump at the first solid table roll. In all cases, however, correct setting of each board is most important and in this respect it is essential to have adequately designed adjustments on the support brackets to permit alteration when the machine is running.

It is usually advised that the leading edge of the first forming board is initially set a fraction of an inch ($\frac{1}{8}$ in.) below the line formed between the tops of the breast roll and first table or grooved roll, while the trailing edge is set on this line. This allows for the wire wrap round the breast roll and ensures that the board is set somewhere near parallel to the run of the wire. When the machine is in operation final adjustment is made and

it is generally considered best that the board and wire are in contact but without pushing up the wire. If the board slopes down towards the breast roll, the sheet may be marked in uneven streaks or worms in the same way that can occur with table rolls when too much water enters the leading side of the nip under the wire. On the other hand, if the board slopes towards the couch it begins to act as a foil and although the suction developed is less than with a table roll an appreciable quantity of water can be discharged at the trailing end of the board which may produce precisely the same sort of disturbances that the board is trying to minimize. Bad alignment or too high a setting under the wire can have an appreciable effect on the drag exerted on the wire so that careful observation of the power used by the wire drive can be of assistance in setting the board correctly.

When using forming boards the slice jet should ideally meet the wire in the gap between the first board and the breast roll. If the jet impinges on the wire too close to the leading edge of the board then considerable discharge may occur at the edge due to the initial influence of the down-ward component of the jet, and this may have an undesirable effect on the wire side surface. If the jet meets the wire actually above the forming board then disturbances similar to those described with a breast roll discharge will occur. The length of the forming board section, particularly if solid, should not be too great or the excessive delay in early drainage may induce skating.

3B.1 4 Relation between wire and stock velocities

Although relation between the wire speed and the velocity of the stock or slice jet (the 'efflux ratio') is known to be of great importance in regard to the degree of anisotropy of the paper, surprisingly little has been published on this topic until recently. Andersson and Bergström (8) were in fact the only authors to have made a specific investigation of this variable, and their work was performed on an experimental machine with an apron slice at speeds ranging from 300 to 600 ft./min. The relative velocity of the stock to the wire was varied by opening up the slice and allowing stable conditions to be reached with the same flow from the breast box but at a new level; the machine speed and substance remained effectively steady. To eliminate the effect of drying strains on the relative machine and cross direction properties of the paper, the web was cut between the couch and first press, pressed between blotters and then dried between polished plates.

Fig. 3.12 shows results obtained at a single speed of 300 ft./min. though these represent an average for various conditions which involved altering the position of the apron and also the suction applied to a forming board between the breast roll and first table roll; these latter variations had some degree of influence on the strength ratio but not of the same order as the relative wire and stock velocity, nor did their alteration appear to change the optimum relative velocity. It is apparent that in the region when the slice jet velocity is some 5 per cent. to 10 per cent. slow, anisotropy in the sheet is at a minimum and other experiments indicated that this remained

substantially the same at higher speeds; this incidentally agreed fairly well with determination of the orientation of a number of coloured fibres which also showed least alignment in the machine direction with the stock velocity about 10 per cent. slow. Judt (48) has also reported that the lowest strength ratio occurs with the stock velocity between 10 per cent. and 15 per cent. slower than the wire speed, though this author also states that look-through and uniformity of fibre deposition is best with the velocities equal.

A fuller investigation has now been reported by Schröder and Svensson (106) in which the effect of changing the efflux ratio in regard to various paper properties was studied on the Swedish Central Laboratory experimental machine and on commercial machines. Various graphs are presented
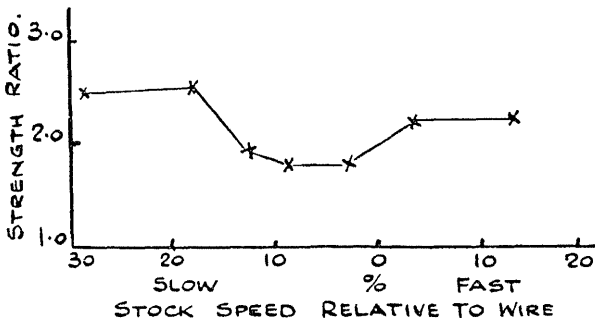
Fig. 3.12. Influence of the relative velocity of stock to the wire speed (efflux ratio) on the strength ratio of paper (after Andersson and Bergström)

and all show a turning point in the relation between the different paper properties and the efflux ratio at the point where this is unity; in this work the jet speed was calculated without allowing for any discharge coefficient and if this were taken into account the turning points occur for the jet speed about 4 per cent. to 5 per cent. slower than the wire (assuming $C = 0.95$ or 0.96) which is in agreement with earlier work. Of those properties tested, tensile and tear ratio, bulk, burst, and breaking length in the machine direction had minima at this efflux ratio, while formation, porosity, and cross-direction breaking length had maxima. Some of the curves are not simple but assume a W shape with a sharp increase or decrease in the region of the critical efflux ratio; this applies especially to burst and rigidity properties, the sharpness apparently becoming greater at higher speeds.

Andersson and Bergström also assessed that earlier and more intense drainage resulting from alterations to the apron and forming board conditions produced a greater fibre orientation, although the general visual formation of the sheet appeared better due presumably to the more efficient deflocculating shear forces operating with rapid drainage. However, if dewatering were delayed and the sheet allowed to form under conditions of moderate drainage then, apart from a better isotropy, a

closer sheet was obtained as indicated by the lower air flow through the suction boxes and higher air resistance of the paper.

From this work it is apparent that the relative velocity of stock to the wire requires close control and this is particularly the case if the sheet is being formed to give least anisotropy, since there are strong indications that small variations on either side of the optimum can often have a considerable influence on the degree of anisotropy obtained. Robertson and Mason (81) have emphasized the importance of this point particularly with regard to the possible influence of local variations across the web. Using a technique for separation of chemical and groundwood fibres in newsprint sheets they were able to demonstrate that a large proportion of samples exhibited alternating regions of orientated and random chemical fibre alignment on the wire side across the sheet; it is quite likely that this was produced on machines operating close to the optimum relative velocity point though in the absence of further details the influence of other factors, in particular whether there was partial breast roll discharge, cannot be discounted as a possible explanation.

3B.2 TABLE ROLLS AND OTHER DEWATERING DEVICES

The original reason for using table rolls on the Fourdrinier paper machine was undoubtedly their convenience as a support for the wire. That they prove to be highly efficient devices for removing water from the web and also apparently have a useful role in assisting good formation of the sheet could be regarded as fortuitous but highly beneficial. But table rolls are not, of course, without their disadvantages and these become more apparent at higher speeds.

3B.2 1 Disturbances with table rolls

The suction forces acting in the nip of a table roll and their effect on the wire and underside of the mat have already been discussed in detail. At the point where the vacuum is broken it is apparent that the wire experiences sharp upward acceleration that will react directly on the fibre mat; this produces an impulse that can have an appreciable effect on the stock surface and produce various disturbances, in particular that known as stock jump. Burkhard and Wrist (21) were the first to investigate the phenomena associated with these disturbances and their observations will now be described.

Using a high-speed ciné-camera it is possible to follow the development of disturbances as the stock passes over a table roll; Burkhard and Wrist found by this means that any small depression existing in the stock surface on approaching a roll increases rapidly in depth over the suction zone. At the end of the suction zone the upward impulse on the mat produces a pimple in the centre of the depression which grows in height to form a sort of spout; this spout falls back relative to the stock surface as it meets resistance from the air and this accelerates a process of breaking up into a spray that consists mostly of fines at a consistency lower than that of the

breast box stock. This is observed on the machine as stock jump and, though directed forwards, the spray of course lands on the wire behind the point where it originated.

The type of depression in the stock surface which can produce kick-up of this nature appears to be caused primarily by small bubbles and irregularities already on the surface of the stock, and also as a result of earlier spray landing on the wire immediately ahead of a table roll. Stock jump can be observed at speeds well under 1,000 f.p.m. but its onset is influenced by stock conditions and other factors. Consistency of the stock is important and Burkhard and Wrist assessed that increasing consistency from 0·6 per cent. to 0·85 per cent. on their experimental machine delayed the start of stock jump by about 500 f.p.m.; a similar effect was observed if initial drainage was made more gradual by the substitution of foils—the mat consistency at the first table roll was then raised and this too delayed onset of stock jump. Other effects observed in this connection were that a temperature increase of 15 deg. F. reduced the critical speed for stock jump by roughly 100 f.p.m., while increased aeration or a lower tension in the wire also reduced the speed at which stock jump was first observed. The probable explanation of these observations lies in the increase in surface tension and viscosity associated with increased consistency and decreased temperature; increasing wire tension will reduce deflection of the wire and the consequent impulsive force on the mat at the point where the suction is broken.

Mardon and Truman (50) have observed that individual ridges in the stock surface approaching a table roll may branch into smaller ridges on either side, while Wrist (84) has stated that even if no pronounced disturbance exists in the slice jet the first table roll or foil will create a regularly spaced set of ridges on the surface and these will be perpetuated in succeeding rolls until they eventually become smoothed out as the mat consistency rises. Theoretical and experimental work carried out by Yih and Lin (99) has shown that these phenomena are an inherent feature of the hydrodynamic instability of a moving liquid surface subjected to vertical forces and small changes in its direction of motion.

3B.2 2 Other aspects of table rolls

Wrist also gives some interesting results of measurements of the power transferred from the wire to a table roll (additional to that used to overcome bearing friction). This power decreases down the wire, corresponding closely to the decline in the quantity of backwater discharged, and increases with higher speeds and with greater flexing of the wire (obtained by removing deflectors). Wrist concluded from these and other observations that most of the power consumed by a table roll goes in agitation of the stock.

Increased drainage is obtained from a table roll by application of a doctor, but generally speaking this is not considered advisable due to the probability of increased power consumption and excessive wear on the wire which will occur if resistance to rotation causes slippage at a number of rolls. In some cases, particularly on slow machines, a table roll may stop

completely and it must be considered poor practice not to remedy this immediately because once a flat is worn on the roll it will become useless for running under the wire; occasionally a roll may be stopped deliberately with the idea of delaying drainage, but this action must obviously be tolerated only as a temporary expedient for it would be more satisfactory simply to remove the roll, if nothing else.

To reduce the drag exerted by a table roll on the wire, anti-friction bearings have come into general use. Rolls have also tended to grow in size to maintain dynamic stability at high speeds; a certain critical speed exists for any roll at which whipping and vibration occurs and this is raised if the roll is of larger diameter and more rigid. A vibrating or eccentric roll can be very troublesome especially close to the slice, and produces barring in the paper.

3B.2 3 Use of deflectors and foils

On faster machines a considerable quantity of water discharges from the nip of a table roll and if this splashes on to the roll following it can produce marks on the wire side of the paper where a stream of water has been carried into the nip. Regular-spaced streaks from the curtains under the wire carrying forward into the nip of the next roll can also affect the appearance of paper.

For these reasons it is common to place a barrier between the table rolls and this is termed a baffle, deflector, or scraper, though the latter description is, perhaps, rather unfortunate. Although the top surface of a baffle must be very close to the wire to be effective, it is not good practice to have the top so hard up on the underside of the wire that it actually scrapes the surface. This can lead to a considerable increase in power consumption at the wire drive, and uneven wear across the baffle will lead to a variable carry-through of water under the wire which can produce streaks. Nevertheless, as a precaution against scraping, the surface of a baffle should be of a low friction material similar to those used for suction box tops.

If the baffle has a comparatively wide surface and is adjusted to slope down towards the couch with the leading edge touching the wire, then a suction is developed in the nip. The device then becomes what is commonly known as a 'foil' and the surface may be $1\frac{1}{2}$ in. to 3 in. long. Individual foils generally extract less water at a lower consistency (loading as well as fibre) than table rolls, except possibly when these are of comparatively small diameter, and they also disturb the surface less; however, they require less room than table rolls with baffles, and in an equivalent wire length a bank of foils (usually arranged in units of three to seven) extracts a greater quantity of water (86, 96, 97, 100, 103, 109, 111). Typical results have been reported by Sisler and Maves (96) who substituted four foil units for three table rolls immediately after a forming board and found, for various substances of a letterpress printing grade, that in every case the total drainage from the foils was greater. These workers also found by adjusting the dip of the foils that an optimum angle (between 2 deg. and 3 deg.) occurred at which the foils extracted most water, and this has been con-

firmed by Roecker (105) who also considers it preferable for the trailing edge of a foil to be straight rather than convex.

However, Descary (103) has reported data which indicate that the optimum angle should be nearer 4 deg. for maximum drainage consistent with least disturbance to the fibre mat, while Hansen (111) recommends the use of increasing angles down the wire, so the question of optimum angle would seem to be in dispute.

One advantage of a foil provided it is not too long is the reduction in stock jump and disturbance to the underside of the sheet at faster speeds; over a foil any depression in the stock surface gradually grows in the same way that occurs over the suction area of a table roll, but the impulse to the wire at the point where suction is broken is much less. For these reasons it has been considered likely that foils might well replace table rolls provided wear on the wire is not excessive. The development of abrasion-resistant plastic surfaces (especially high-density polyethylene) for foils has reduced considerably the wear and drag on wires, and foils are now used solely on quite a number of machines. However it is often thought, as described in 3A.2 3, that some table roll action is important to maintain the formation of the sheet, and it has also been observed that the advantages of foils diminish as they are substituted for more and more table rolls on a particular wire section. Nevertheless, the application of foils is becoming increasingly common in the wire section and they are now used success-fully on many high-speed machines in the early part of the drainage area where it is particularly desirable to reduce the amount of stock jump and at the same time increase the overall rate of drainage. At medium speeds the substitution of foils for table rolls at intervals in the wire section is often particularly advantageous because the lower consistency of backwater removed by foils results in a higher retention of loading and fines, and some reduction in two sidedness and increases in burst and air resistance have also been reported. The increased drainage rate and lower backwater consistency both assist in lowering the consistency of the breast box, which can be useful for forming the sheet more satisfactorily or retaining quality.

3B.2 4 Other drainage devices

In previous discussions it has been emphasized that rapid drainage in the first few feet of the wire section is generally undesirable; stock jump is closely associated with rapid drainage and the need to minimize such disturb-ances is a further reason for delaying drainage. Apart from the foil, two main modifications to the table roll serve this purpose, the grooved roll and the dandy-type roll. Of the two, the grooved roll is most popular and is easiest to run provided the groove is spiralled and preferably terminates sufficiently far from the roll end to avoid any possibility of catching the wire edge. In varying degrees either device generally removes less water, at a lower consistency, than a table roll, and their use in the early part of the wire serves the dual purpose of making drainage more gentle, thereby permitting the bottom layers of the mat to be formed without undue

violence, and allowing the consistency of the mat to increase to a point where stock jump is less likely above the first table roll.

The use of grooved rolls and the other devices is largely a matter of individual experiment and unfortunately it is frequently difficult to draw definite conclusions as to the effect of their use in different positions. Too many foils or grooved rolls before the first table roll may prevent excessive stock jump but at the expense of loss of formation. More frequently the problem arises that the use of grooved rolls so reduces the dewatering rate as to bring in complications similar to those encountered in trying to speed up a machine with an inadequate wire drainage capacity. It is not possible to cram rolls together too closely or there will be insufficient space for water to escape between the roll and baffle. Larger diameter rolls extract more water but only approximately in proportion to the space they need. Experiments involving carefully controlled alterations to the various factors which have been discussed above have been reported by Hendry *et al.* (3), Duskin (18), Burkhard and Wrist (21), Parker (68), and Wrist (84), to which reference can be made for further details.

The problem of dewatering on an existing wire part has lead recently to the introduction of several special devices designed to increase water removal by the application of vacuum. One arrangement (102) applies a light vacuum of a few inches w.g. to a conventional foil unit and is claimed to give a considerable increase in dewatering on slow stocks or high sub-stance sheets run at relatively low machine speeds, conditions in which foils without vacuum do not perform so well. 'Forming boxes' or 'wet suction boxes' are a similar device except that the surface contacting the underside of the wire is flat, as with forming boards, instead of angled on the trailing side. Experimental work on these units (98, 107, 108) has indicated that increased drainage occurs except when the web is very close (greaseproof and other wet-beaten furnishes), and also an improvement is seen in strength and other properties of the paper and there is a more even distribution of fines and loading through the thickness of the sheet. How-ever, earlier work reported by Parker (68) noted a deterioration in forma-tion when this type of box was substituted for table rolls on a fast machine, though flow on the wire was free from the normal disturbances encountered at higher speeds with table rolls. A third device employs vacuum on a number of conventional table rolls to which appropriately designed end-seals are applied to retain the vacuum. This is also claimed to improve drainage rate.

It is in fact likely that any arrangement allowing a vacuum under the wire will increase drainage rate, but only up to the point where the vacuum induced by the natural action of table rolls or foil units remains lower than the vacuum applied. With flat-surfaced forming boxes no natural vacuum would normally be experienced, but here the time available for the imposed vacuum to be felt can be expect to limit its effect. There is thus likely to be an upper limit to the machine speed at which these devices will effect useful improvement in drainage by provision of an economical and practicable vacuum. However, when a useful improvement in drainage can be obtained an added facility is that variation of the strength of

vacuum can be used to adjust the drainage rate, thereby permitting reasonable changes in wetness on the wire to be corrected without having to alter the breast box consistency.

3B.3 SHAKE

Of all aspects of papermaking on the slower Fourdrinier machine none is more individual to each machine than the operation of the shake. It is not then surprising that a survey of the literature soon brings to light a considerable diversity of views on the value and attributes of shake. For instance, some consider that shake has most effect over the first few table rolls, others that it is of relatively little importance until later on (hence, incidentally, the reason for attempts to apply the shaking force to the wire near the suction boxes instead of at the breast roll). Some authors state that the application of shake causes water to be removed more rapidly, others that the opposite effect occurs, while a third body of opinion holds that a slow shake promotes drainage but a quick shake retards it. Yet again, some consider that shake increases anisotropy of the sheet, others that it improves evenness of fibre orientation and directional strength properties, and similar differences of opinion no doubt also exist as to whether shake serves any purpose at all.

When it comes to advice on how to operate the shake on a machine, in particular what length of stroke to use and what frequency, it is certainly a case of 'comment is free, but facts are expensive'. Laboratory simulations have been attempted to throw some light on the subject but though they lead to more consistent results within themselves their value as a guide to what happens on the paper machine cannot be considered great. The worker who has done most to throw a gleam of light on this subject is Judt and what follows is largely a summary of his researches (47, 48).

3B.3 1 General effects of shake

Judt has made a direct investigation of the operation of shake in more than one hundred experiments on six fine paper machines mostly running at speeds within the range 100 to 300 f.p.m. The results obtained from the mass of data collected in this work may be conveniently summarized as follows:

(a) Evenness of fibre orientation and also, to some extent, the ratio of strength tests in the machine and cross directions improve with application of shake, though the effect diminishes at higher speeds; improvement in fibre orientation is greater with wet stock and on the top side of the sheet.

(b) Drainage of the mat with free stock is retarded by shake, particularly in the early part of the wire, and the effect is increased by a faster shake; for wet stock, shaking increases the drainage rate and again the effect is greater with a faster shake.

237

(c) Formation improves with application of shake though the effect diminishes at higher machine speeds; this improvement is greater for wet stocks and is present up to greater speeds than for free stocks.

(d) Formation improves with increasing frequency and stroke of shake though a point is always reached where further increase brings about a deterioration; the shake is also more effective when the substance is heavy and the breast box consistency high.

(e) With the stock velocity equal to the wire speed shake can cause a deterioration in formation; with the stock velocity lower than that of the wire by a few per cent. this does not occur.

(f) When application of shake has a positive effect on the formation, and anisotropy of the sheet is reduced, then the density, burst, air resistance, and average stength of the paper all increase; this effect diminishes at higher speeds.

(g) Increasing the amplitude as opposed to frequency of the shake has more influence in increasing the density and average strength properties of the sheet; increasing the frequency of shake has more effect on the formation.

It is apparent from these results that there are many complications involved in defining the effect of shake. The basic reason for this is undoubtedly that shake influences any particular sheet to an extent dependent essentially on how much improvement it is possible to make; in other words shake has the largely negative purpose of remedying the deficiencies (particularly of flocculation) present in the stock as it flows on the wire, and of inhibiting the development of flocculation during drainage. The quality of the stock, in particular whether it is free or wet, and the design of the wet-end of the machine itself must therefore have considerable influence on how effective shake proves to be under any particular circumstance. At higher speeds improvements in the approach system and breast box design, the use of shorter fibres, and increased agitation on the wire all reduce the tendency for flocculation to occur; this, more than the mechanical difficulties involved in increasing the shake speed for corresponding increases in machine speed, has probably been responsible in the past for shake being found unnecessary on faster machines.

Turning to one or two specific points, it is possible to give a general explanation for most of the items listed above; attention will, however, be confined to three of the more important effects. Firstly, for shake to be effective in improving formation and producing a more evenly aligned sheet it must act on the fibre mat for a sufficient time; hence, in general, the reduced effect observed with faster draining free stocks and at higher speeds. Secondly, when the sheet is difficult to form on the wire without flocculation, e.g. when the substance is heavy or the breast box consistency is high, then shake can be particularly effective; also improvement is likely to occur particularly on the top side of the sheet which is normally the more flocculated due to the longer time the upper layers of fibre remain in suspension. Thirdly, as regards the different effect of shake on the drainage rate of free and wet stocks, it is probable that for free stocks the rate is slower with

shake due to the formation of a denser fibre mat on the wire, particularly in the wire side layers; for wet stocks on the other hand the tendency to compact down quickly on the wire side, producing a mat with low permeability that retards drainage, is hindered by shake which tends to keep the mat more mobile.

These points by no means explain all the varied observations presented by Judt and, in particular, nothing has been said regarding the reason for the different effect of shake amplitude and frequency although it is obvious that these, by governing the relative velocity between the stock and wire at different points, are highly important. Judt has evolved several ingenious hypotheses to explain the varied effects he noted and the interested reader may care to refer to the original papers for a fuller treatment of this subject; for the present purpose, however, the author sees no value in attempting to present explanations for observations that are not necessarily general, nor of much practical significance.

3B.3 2 Other observations on shake

Several of the results obtained by Judt have been observed by previous workers and of these four investigations are selected for further consideration because they contain some further points of interest.

Brauns, Bergström and Svenson (10) carried out an investigation into the effect of shake on an experimental machine with an apron. A comparison with and without shake indicated that paper made with shake in general had less fibre orientation and was less flocculated. Increasing the amplitude of the shake beyond a certain point, however, produced an increased fibre orientation in the machine direction. Both the amplitude and frequency govern the accelerating force applied to the wire and if either is made too great formation begins to deteriorate and a point is reached where waves appear on the surface and the sheet is liable to become completely disrupted.

Hitchings (26) is another worker who investigated the effect of varying shake frequency and amplitude on a slow paper machine with particular reference to the effect on drainage. He found that applying shake decreased the drainage rate and that increasing the amplitude of the shake with frequency constant caused first less, then more water to be removed from the table rolls until a point was reached where the drainage rate became almost equal to that observed without shake. Increasing the frequency of shake with amplitude constant had a fairly similar effect. From his results Hitchings claims that there exists a combined optimum level of frequency and amplitude, which he terms the 'total shake speed', at which the drainage rate is a minimum; this condition then results in maximum strength properties in the sheet.

An unusual investigation has been reported by Finger and Majewski (11) who sought, by stripping off successive individual layers of fibres from a sheet of paper, to compare the average fibre orientation at different points within the thickness of the paper. By this means they succeeded in demonstrating that the frequency of shake in relation to the distance between the

table rolls can produce an observable effect on the orientation in different layers. If, for instance, the time taken by the wire to travel between two consecutive table rolls is a multiple of the time for a single shake oscillation, then the relative velocity of the stock and wire is always the same for any particular position on the wire when it passes over a table roll. As the average orientation of fibres is influenced by this relative motion it is apparent that fibres will then tend to be deposited above one another in the same general direction at each roll; this effect will produce a waviness in fibre alignment along the length of the sheet. Other relationships between the shake frequency and the time taken to travel between two consecutive table rolls produce different effects on the sheet. In general a cyclic variation in average fibre orientation exists through the thickness of the sheet though it tends to become blurred towards the top side due to the reduction in drainage rate, the smaller relative motion produced by the shake, and the unevenness of the thin layers deposited.

Finger and Majewski conclude from this that certain conditions of frequency and amplitude of stroke are critical in determining the basic structure of the sheet both in the machine direction and through its thickness. On any machine there will presumably be a range of speeds where this effect becomes more prominent. At very slow speeds relatively little extra drainage occurs at table rolls so the suction impulses necessary to produce a predominant fibre orientation at particular positions will be absent. At faster speeds, of course, the diminishing influence of the shake as a whole will also reduce the significance of this particular phenomenon.

Finally, Manson (90, 113) has presented some data on the effect of shake on formation, as measured on a laboratory test instrument, which further confirm the complexity and contradictions surrounding the use of this device. In his first experiment the amplitude of the shake on a very slow machine was reduced from $\frac{3}{16}$ in. to $\frac{3}{32}$ in., and finally the shake was stopped altogether. The surprising result emerged that although overall formation was worse without shake than at the original setting, halving the amplitude to $\frac{3}{32}$ in. worsened the formation to an even greater extent.

Manson also investigated the effect of removing shake on a faster (900 ft. per min.) machine. Even at this speed, at which shake is normally considered to have relatively little effect, an observable deterioration in formation was measured without shake. The effect was not, however, so great as was caused by the removal of the dandy, see 3B.5 1.

A later analysis of the effect of shake on a variety of grades of paper run at speeds ranging from 300 to 1,000 ft. per min. indicated that formation improvement is related to the product of amplitude and the square of the frequency of shake, and is less at higher machine speeds; however, the effect of shake was often found to be erratic and sometimes there was little improvement in formation. The effectiveness of shake was reduced at higher breast box consistencies or if the refining degree was increased drastically. When improvement occurred it was generally found to give a more even distribution of fibres and reduction of clumps in regions spaced $\frac{1}{4}$ in. to 2 in. apart.

3B.4 SUCTION BOXES

In this section it is proposed to deal primarily with two aspects of the use of suction boxes which have a close bearing on their efficiency of operation. Firstly, the frictional resistance and abrasive action of suction boxes on the wire will be considered; as these affect the rate of wearing and the over-all vacuum which can economically be applied to the boxes they are of obvious importance to the working efficiency. Secondly, attention will be given to the method of application of vacuum; this is of importance in determining the flexibility of operation of the boxes although other questions such as that of ease of assessing performance and general stability have also to be taken into account.

3B.4 1 Frictional resistance at the suction boxes

The effect of abrasion between the wire and the suction box surfaces is threefold: power consumption to rotate the wire is increased by the frictional resistance, the wire is worn rapidly, and the suction box surfaces are also worn. Generally speaking, each of these factors can be expected to increase in degree with higher speeds, and on high-speed machines the rate of wire wear particularly can become a difficult problem. It has been found on faster machines that between 50 per cent. and 70 per cent. of the total load required to revolve the wire section is due to frictional resistance at the suction boxes. The importance of minimizing friction is therefore clear; this topic will be considered first.

The resistance of the wire to passage over the suction boxes depends essentially on two factors: the total load acting between the wire and box surfaces, and the coefficient of friction. Apart from the relatively small load due to the support given to the wire by the suction boxes, under any particular running conditions the effective load is dependent entirely on the vacuum applied to the boxes and so may be expected to increase almost proportionally with the vacuum. The coefficient of friction, on the other hand, depends on a number of variables including the materials of the boxes and wire, the pressure between the two (i.e. the relation of the load to the supporting or land area of the boxes) and any lubricating action that may result from a film of water under the wire. The question of materials is closely allied to the problem of wear and is conveniently left till the next section, but apart from this aspect some other useful experimental results relating to the friction coefficient have been reported.

Macdonald *et al.* (49) have carried out an extensive survey of the factors affecting wire wear and this will be considered in greater detail in **3B.7 1**; for the moment attention will be confined to that part of the work relating to the suction boxes. In this, the load on each of the boxes of several paper machines was determined by relating the vacuum to the open area, while the drag on each box was found by observing the reduction in power consumption which occurred when vacuum on the box was gradually lowered to zero (the vacuum on the other boxes being readjusted to their original value, if necessary). As a matter of interest no further observable

reduction in power consumption occurred if a box were lowered from the wire, which confirms the negligible effect of drag caused solely by the weight of the wire on the box surface. This technique, though simple, gave good correspondence with a direct measurement of the drag experienced by a suction box when operating normally (this was obtained by using strain gauges incorporated in the supports), and any change to other running conditions brought about by shutting off one of the boxes was not considered to be of significance.

Results from this work indicated that the coefficient of friction increases as the percentage open area in a particular box is reduced, or if the vacuum is reduced, i.e. in both cases if there is a lower pressure on the box. Put another way, this implies that an increase in the load between the wire and boxes does not give a proportional increase in the drag. The coefficient of friction also increases as a wire ages; this is probably a direct result of the lower pressure produced by spreading the normal load over the greater area of wire exposed from wearing down of the knuckles. The increase in power consumption observed as a wire ages is mainly caused by this change in frictional drag at the boxes.

Macdonald found no difference in coefficient of friction according to the position of the suction box, i.e. whether at the wet or dry end. Generally wet boxes had higher friction coefficients than dry, but this was no more than could be accounted for by the difference in pressure (the vacuum was usually lower for one thing). It therefore appears that if there is any lubricating action due to a water film, it is present fairly equally at all the boxes irrespective of the solids content of the web or the quantity of water removed.

All the results quoted above have also been found by Boadway (42) on a small experimental machine. This worker observed in addition that speed of itself did not appear to affect the coefficient of friction.

Macdonald also observed that a freshly dressed box had a relatively high coefficient of friction until the surface became bedded in; because of this it is prudent to take care during resurfacing to prevent any unevenness (in particular to support the box at the ends, as on the machine, when planing or grinding), and whenever possible to change only one box at a time to prevent excessive drag on the wire.

From these results the useful conclusion can be drawn that the greater the proportion of open area in a box the better, and this is so especially for dry boxes which carry a higher vacuum; fortunately this agrees completely with the requirement that the gap between consecutive suction zones should be as small as possible. Thus in practice the individual slots or holes in a box should be separated by a minimum of solid surface compatible with the demands of rigidity. This applies especially to the cross-machine edges of boxes where an unnecessarily wide land area represents a useless increase in drag.

A further point that is clear is that the proportional drag experienced by the first few boxes will be higher when these are run at a lower vacuum. This does not mean that the vacuum may just as well be as high as in late boxes, because the increase in total load resulting from this would more

than offset the slight decrease in friction coefficient at the higher vacuum and produce an unnecessary increase in total drag on the wire; rather the implication is that the vacuum in the first few boxes should not be reduced too much, particularly if this leads to the need for greater vacuum in later boxes. The staggering of vacuum should, in other words, be gentle.

3B.4 2 Abrasion of the wire and suction boxes

Abrasion of the wire and the box surfaces causes wear to both, and in selecting appropriate materials the rate of wear in each case must be considered. A suction box surface material that offers a low coefficient of friction and low rate of wire wear is no use if the material itself wears away rapidly and requires frequent dressing and replacement. The rate of wear of both wire and boxes can be expected to increase with the vacuum applied at the boxes and, in fact, with any other factor which increases the drag. The quantity of abrasive material in the stock, especially loadings and grit coming from the grinding stones used in mechanical pulp, also affects the rate of wear; this applies especially if the material can become embedded easily in the box surfaces and also, according to Boiteux (24), the abrasive effect depends (at least for loadings) mainly on the particle size. If wear is uneven due to the boxes being out of line or tilted, or particularly if uneven wire tension is allowed to wear hollows into the box surfaces, then frequent resurfacing will be necessary, the vacuum may be lost, and it may also become difficult to keep the wire straight. It is now, of course, common practice to avoid the possibility of grooving from individual wire warp strands by oscillating the boxes laterally, though a more modern alternative is to use a wire guide which gives the wire a continual positive oscillation from side to side. Another device which is claimed to avoid the necessity for frequent dressing of box surfaces and to ensure a good seal involves the use of flexible hollow ribs which are pressurized with water or air. These ribs form cross-machine slots and can be renewed by sliding out of a retaining groove.

The most common material for suction box surfaces for many years has been hardwood, particularly end-of-grain maple, which may be wax impregnated. Under normal conditions with the usual phosphor-bronze wires this has given a tolerably long life, but with increasing machine speeds the relatively high coefficient of friction of this material causes the frictional drag and rate of wire wear to become excessive. Much research has been conducted into finding a more appropriate material and many different covers are now on the market. Some reports of changes in cover material on individual machines are available, but the most thorough assessment has been given by Lawson and Lambert (78), who have carried out extensive laboratory and machine comparisons. Rubber covers, for instance, apparently wear less than hardwood but have too high frictional drag; plastics like nylon and teflon (fluon) are more satisfactory, while overhard boxes made from steel, ceramic, glass or aluminium are likely to cause too much wear to a metal wire. The results of Lawson and Lambert indicated that high-density silicon carbide covers give the best all

round performance; of all the materials they tested these apparently had the lowest coefficient of friction and wearing effect on the wire, while lasting longest and also having a good resistance to accidental damage. However, this material is very costly, and an alternative which does not require the same capital outlay is high-density polyethylene. But it would be unwise to generalize and conditions are likely to vary substantially from one machine to another, necessitating individual trials to determine the most suitable from the many materials now available commercially.

In theory the most economic choice of material would minimize over a period the combined cost of labour and replacement of both the wires and suction box surfaces, together with the average power consumption required to overcome drag between the two. On fast machines particularly this implies, more than anything else, the necessity of reducing the friction coefficient and keeping wire wear and the frequency of box dressing to a minimum. Plastic, chromium-plated or stainless steel wires will no doubt require different suction box materials to those most suitable for phosphor bronze wires, but at least for faster machines it seems likely that specially developed surfaces will soon gradually replace the traditional materials. Whatever material is used it is also, of course, essential that it can be resurfaced satisfactorily and is sufficiently rigid to permit a low ratio of land to open area.

3B.4 3 Rotary belts over the suction boxes

One method of overcoming the problem of abrasion between the wire and suction boxes is to interpose between the two either a perforated or slotted neoprene belt or a coarse plastic fabric which runs in contact with the wire; this is supported separately and is designed and lubricated to minimize friction and wear over the box surfaces. The belt types are the only ones about which there have been any operational reports and these have invariably stated that much less power is required to rotate the wire and that wear on the wire is greatly reduced. Generally installations appear to be placed over boxes at the dry end because it is in this region that the higher vacuum used produces most drag.

Although applications at quite high speeds have been reported, it would seem that difficulties can occur in trying to keep the belt rotating satisfactorily without flying off. Also it is apparently not always an easy matter to guide the belt and the wire (which usually drives the belt), while a special tray may be needed to catch water thrown out of the belt perforations. Even so, Mills (60) has estimated that the capital cost of a Rotabelt rotary belt unit on one high-speed machine was recovered in eighteen months to two years as a result solely of the reduction in wire costs, and Friese (54) has also given a satisfactory report for a slower machine. Application of the Beloit Flo-Vac model has been described by Hill and Clark (65) and Smith (82) and similar advantages are claimed.

Smith, in particular, gives a detailed account of the problems encountered in substituting a rotary belt for three 'dry' suction boxes and making it operational. The eventual reduction achieved in wire wear (40 to 50 per

244

cent.), and lower power consumption required to drive the wire section (30 per cent.), made the device particularly beneficial in this case because originally it was a difficult problem on the machine concerned to obtain an adequate wire life. Experience with this particular model lead to replacing the rollers originally holding the belt with stationary guides: the belt itself was made from neoprene reinforced with nylon cord, while teflon surfacing appeared appropriate for the suction box covers. Guiding the belt, and the appearance of fine wet streaks on the wire, gave considerable trouble at first until the lubricating water used to float the belt over the boxes was reduced in quantity and the application method modified to give a more even spread of water across the belt. Life of the belts up to the date of the report was only five months and replacement was generally necessary due to wear and cracking at the edges; it was, however, expected to improve on this.

One final point should be noted with regard to the rotary belt. Although several general statements have been made that water removal is improved, so far as the author is aware no figures have been quoted to illustrate this. The general assumption is that since the use of a belt permits a much higher vacuum to be applied (12 to 15 in. Hg.), then water must be removed from the sheet more effectively. But it has been seen earlier that the scraping action at the trailing end of the open areas in a suction box is responsible for removing probably the majority of water, certainly on faster machines. This scraping action on the underside of the wire is absent when a rotary belt is used and is replaced by a scraping action between the belt perforations and the suction boxes which cannot be expected to produce the same effect. It would, therefore, be interesting to learn by direct comparison whether in practice the greater vacuum that can be applied through the belt perforations offsets a probable reduction in the scraping action effect.

A different method of overcoming abrasion between suction boxes and wire is to remove the boxes altogether and substitute hard-rubber-covered rolls underneath which run soft-rubber rolls in contact along the full length, the 'Rolvac' system. Vacuum is then applied to the volume formed by the three rolls and the wire, with an appropriate sealing deckle at the edges. As with rotary belts, the absence of scraping action under the wire will diminish the efficiency of this device unless high vacuums are used, but there is no doubt that wire life is extended to a high degree.

3B.4 4 Application of vacuum to the suction boxes

On older machines suction is applied directly to the upper section of the box through a pipe connected to the underside in one or more places. But nowadays it is more common for the box to be divided lengthways by a plate in which there are several large connecting holes or slots, and suction is then applied at one or both ends of the box. Alternatively the box may be divided only at the ends to carry the deckle seals in the upper compartment, and incorporate in the body of the box a number of sloping baffles. Whatever the design the object is to ease removal of water from the box,

give a more even suction across the web, and permit individual boxes to be taken out quickly and easily.

The method of applying suction to the boxes varies considerably but particularly on older machines a popular arrangement involves connection of each box to a manifold which leads to a large separator tank to which suction is applied by the pump. Regulation of the vacuum in such a system broadly follows one of three ways: manual operation with release valves usually at the back side of the machine, together often with a fine adjustment admitting air through cocks at the front; by a spring-loaded vacuum release mechanism which in effect sets an upper limit to the vacuum in the system determined by manual setting of the spring pressure; or by a controller which maintains vacuum at the desired level, for example by letting more or less air into the system. The first system is the crudest and allows only a rough setting of the vacuum which furthermore tends to become unevenly distributed across the web especially when air is admitted at the front side. With the spring-loaded release a more sensitive setting of vacuum is possible though in this case, as in the previous arrangement, considerable quantities of air are likely to be sucked from atmosphere and this increases pumping costs.

The spring-loaded mechanism is often used largely as a precaution to put an upper limit to the vacuum that it is possible to apply. In this event the vacuum will, to a certain extent, vary with the closeness and solids content of the web, i.e. the less porous the web and less easily air is sucked through, the greater will be the vacuum applied. In this case, therefore, a compensating action exists in which stronger suction is applied to a web which is damper or more resistant to dewatering, thereby reducing variations in solids content at the couch; this is probably the most convenient system on slower machines running well beaten furnishes and heavier substances. The fully controlled arrangement on the other hand keeps the operation steadier, particularly with regard to drag on the wire and hence draw at the couch, and permits the vacuum to be set and kept precisely at a level which is most economical from the point of view of wire wear versus drainage capacity; for these reasons this system is more suitable for faster machines.

Drop-legs can be placed on a box to assist direct removal of the water before it enters the separator tank manifold; this requires sufficient depth available by the side of the wire for the height between the box and the seal-pit level at the bottom of the drop-leg to be greater than the equivalent water column of the highest vacuum applied, otherwise the boxes will flood. Using a manifold and separator tank with assistance of one or more drop-legs is a relatively trouble-free method of applying suction to the boxes so long as adequate precautions are taken to maintain the water level in the tank steady and, of course, below the level of the manifold pipe inlet and the boxes. This requires either a simple level control device in the separator tank, or a level sight glass which is used to adjust manually a valve on the discharge side of the extraction pump. One disadvantage of this system is that observation or measurement with any accuracy of the flow from individual boxes is not possible. Also, since it necessitates throt-

tling the suction inlets, the vacuum on individual boxes cannot easily be adjusted without risk of flooding the box. Uneven application of suction across the machine is likely if the valve on any particular box is partially closed, and oscillations in vacuum which give rise to instability of operation are possible.

In more modern installations these disadvantages are overcome by separate application of suction to each box. This requires a drop-leg on each box (usually at the back side of the machine but occasionally if the flow is large in the first one or two boxes a second leg may be placed at the front side for assistance); the maximum suction available is fixed by the height of the drop-leg but this restriction can, if necessary, be overcome by evacuating the receiver tank at the bottom. A suction inlet is connected vertically above the drop-leg, with the pipe from the suction box joining at right angles, and the individual suction lines connect to a common manifold joining the vacuum pump. Suction on each box is then individually controllable either by a straight-forward valve in each suction line together with a main vacuum controller in the pump, or, as in the Broughton system, by a more elaborate control mechanism which serves to keep losses in the vacuum system to a minimum (in some cases a separate suction box vacuum pump can be dispensed with), and is claimed to have greater stability.

The drop-legs require careful sizing: too narrow a diameter will cause the leg to back up and flood the box, too large and it gives no assistance to the vacuum pump which must then keep a greater volume evacuated to maintain the required suction. Arrangement of the drop-legs can be in a variety of ways but the most useful system involves dropping each leg into an individual compartment; the flow from each leg can then be arranged to pass over a weir into a common pit thereby giving a visual indication and permitting, when necessary, easy measurement or even a record of the flow from each suction box. A further advantage of this arrangement is that separate use can be made of the water flow from the first one or two boxes to maintain the main backwater pit level, leaving flow from the remaining boxes to enter the whitewater system in the normal way.

3B.5 THE DANDY

The function of a dandy is twofold: to improve the formation of the sheet and to give a watermark when required. Stated thus the matter appears simple, but it is no exaggeration to say that used incorrectly or inappropriately the dandy can have both an adverse effect on the quality of the sheet and cause a great deal of downtime. Consideration will be given first to the effect that a dandy running satisfactorily has on the sheet, and this is followed by a brief discussion on the best way of achieving this end and on the special requirements for watermarking.

3B.5 1 Effect of using a dandy

It is generally agreed that running a dandy in the correct position down the

wire brings about a considerable improvement in the appearance of the top side of the sheet. This is particularly true with longer-fibred stock made on slower machines where flocculation of the stock in the upper layers of the fibre mat is more likely to spoil the sheet; the dandy helps to deflocculate these upper layers and spread out any thick lumps that protrude on the surface due to uneven deposition and drainage.

A further effect of the dandy is to consolidate or compress the sheet. When a dandy is lowered on the wire the dry-line will generally recede down the machine; this indicates that the sheet has been closed up making dewatering at the suction boxes more difficult. One result of this should be to improve the wet-web strength at the couch (provided operation is adjusted to attain the same moisture content) and to reduce porosity of the paper, though it is doubtful whether a significant increase in final strength also occurs.

Despite the common use of a dandy it is only relatively recently that any quantitative data on its effect on the quality of paper have been published. Manson (90) has compared the formation (using a laboratory instrument) of paper made with and without a dandy; in each case samples at various positions across the web were measured and the experiment was carried out on different grades from five paper machines covering a speed range from 130 to 1,300 f.p.m. In every case overall formation proved worse without the dandy, though general uniformity across the web was unaltered. The maximum effect appeared to occur for variations in formation having an amplitude of between $\frac{1}{8}$ in. and $\frac{1}{2}$ in.; large-scale variability was relatively unchanged by the use of the dandy. This work very satisfactorily confirms the general impression that the dandy 'closes up the sheet'.

An extension of this investigation at higher speeds has since been reported by Luhde (112). This involved assessing the effect of a dandy on an experimental machine running a coating base grade at four speeds, in steps from 1,200 to 1,800 ft. per min. Formation was measured with the same instrument, and in addition the sheet was split into four sections and photographed in transmitted light. Comparison of results obtained at the different speeds indicates that the dandy caused a definite improvement in overall formation, though the effect diminished at higher speeds and at 1,800 ft. per min. had virtually disappeared. Porosity of the sheet was reduced with the dandy; vacuum on the suction boxes increased, as did fines content in the suction box water. The top layer of the sheet showed a marked change with the dandy down, the visual denseness increasing, fibre clumps becoming less well defined, and a slight increase taking place in the proportion of fines and loading (the latter being already some three times greater than on the wire side). The presence of fibre clumps was always more pronounced in the top side compared to the wire side, though with increased machine speed the top side became as well dispersed as the wire side. Luhde interprets these results as giving evidence of a lateral squeezing action in both machine and cross directions, and the general benefit of the dandy in compacting the sheet and improving appearance on the top side of the sheet is confirmed by this work. However, a disadvantage to using the dandy appeared in the development at higher speeds of a

prominent wire mark. This in fact became so serious that at 1,800 ft. per min. the mark even penetrated into the wire/middle section. Luhde assessed that any improvement in formation the dandy gave when run at a speed over about 1,400 ft. per min. may well be outweighed by deterioration in appearance caused by the intensity of the mark.

It is highly important that the dandy is correctly positioned in relation to the solids content of the web. It is normally placed on the web in front of the dry-line to ensure that there is a water film on the surface. If the web is too wet the dandy, particularly when heavy, will tend to press too
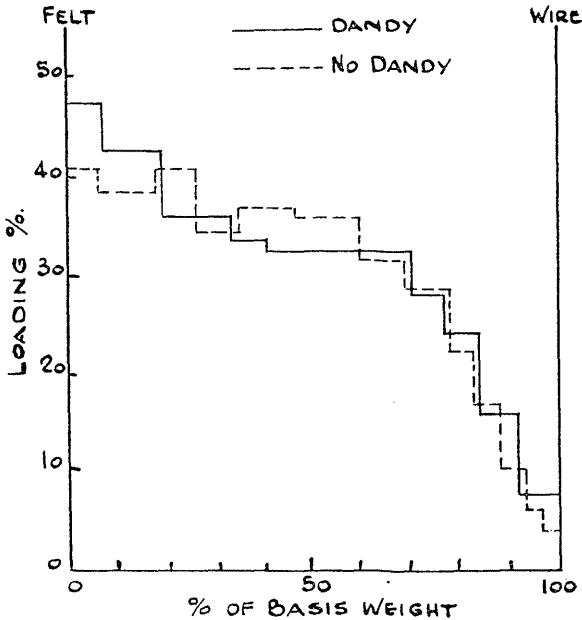
Fig. 3.13. Distribution of loading through the thickness of a paper made with and without a dandy (after Groen)

deeply into the mat; this produces a bulge in the surface of the sheet on the leading side of the dandy which disrupts the upper layers, spreads the whole sheet outwards, and at higher speeds produces a heavy spray which, especially with coloured papers, marks the sheet. On the other hand, if the web becomes too dry the dandy will have less and less effect.

One aspect of the importance of correct solids content of the sheet beneath a dandy has been illustrated by both Hansen (1) and Groen (75) in their work on the distribution of loading through the sheet thickness. With an appropriate film of water on the mat surface a typical change in the distribution of loading produced by a dandy is shown in Fig. 3.13; the concentration in the uppermost layers is substantially increased at the

expense of lower layers (even to the extent of becoming higher than the percentage of loading in the breast box stock), an effect due presumably to the results of compression. If, however, the dandy is run at a position further towards the couch, then this change in distribution becomes much less noticeable, showing that the dandy has less effect on a dry mat. Fig. 3.13 also shows, incidentally, that by increasing the loading concentration on the top side (which has already a higher percentage than the wire side) the dandy accentuates two-sidedness in composition; with some papers the effects of this could represent a distinct disadvantage.

The weight of the dandy creates a slight sag in the wire which will increase wear at the leading edge of the next suction box after the dandy. For this reason a dandy is preferably supported either by a single or a couple of special table rolls inserted between the suction boxes, or above the solid portion of a suction box. The position or pressure of the dandy on the wire particularly at higher speeds must be finely adjustable to give just sufficient contact to drive the dandy. Excessive pressure creates an unnecessary disturbance in the upper layers of the sheet, producing a similar effect to running the dandy with the web too wet. Too light a pressure results in a speed differential between the dandy and the wire, which will scuff the surface and completely spoil the appearance of the paper

3B.5 2 Running the dandy

The problems involved in running the dandy satisfactorily are nearly all accentuated by speed but some, apart from the watermarking aspect, can be present at all speeds. On all machines the dandy tends to pick up fibre, especially at the coarse deckle edges, and this gradually builds up to clog the mesh of the dandy (which is normally coarser than that of the wire). Pitch can act in a similar manner though this is less easy to observe on the dandy. A second problem is caused when froth is generated, creating bubbles of air on the surface of the stock and the dandy itself. Either of these effects produce familiar thin and transparent marks on the top side of the sheet, either singly or in the form of long worms.

These defects are usually obviated by blowing one or more steam and water sprays through the dandy, probably with extra force at the edges, and draping a piece of felt as a wiper on the top of the dandy. A tray may also be used to collect the fibre and froth dislodged from the dandy but it may still be necessary to lift the dandy at intervals for cleaning with a suitable solvent and jetting with steam and water. Because the action is more gentle and the dandy mesh digs into the sheet less, picking and bubbles are not so likely to occur with a larger diameter running with only a light pressure on the mat. But if the dandy is run too dry or the mesh is too fine then, especially with a laid dandy, picking will become very troublesome.

On faster machines the problem of running the dandy fast enough to prevent scuffing of the top surface and the production of excessive spray becomes acute. To bring the dandy up to speed before lowering may be difficult enough in the first place but to keep the running speed close to that of the wire may require such a heavy pressure as to disrupt the mat

anyway. The only adequate solution to this problem is to provide a separate drive for the dandy, and for the larger shaftless type normally in use on faster machines this is most conveniently arranged at the back side of the machine. Either a timing belt running round an appropriate gear on the end of the dandy journal is used, or a direct drive an to one of two revolving rollers which also serve to support the dandy. The drive requires a flexible connection to permit vertical movement of the dandy. Control of the relative speed of wire and dandy should be reasonably fine and is accomplished with a variable speed drive controlled either from tacho-generator references on the wire drive and the dandy motor, or by governing the torque transmitted to the dandy. It may then be found that the best results in formation and watermark are obtained with the speeds the same, but it is possible to find an improvement with the dandy running faster or slower than the wire. There will, of course, be an interaction effect between the speed differential and the pressure of the dandy on the wire so it is advisable at the same time to measure and control the latter. This is usually done indirectly by using the relieving pressure of air in a cylinder or Airide spring arrangement. Adjustable stops restrict the lower limit of movement of the dandy to a position a few thou clear of the wire.

3B.5 3 Watermarking

Under some circumstances it can be very difficult to obtain a good watermark, though generally speaking all the factors mentioned above as contributing to satisfactory running of the dandy have a similar effect on the watermark quality. Thus, the mark has a watery appearance and is distorted by the dandy sitting too heavily on the mat, running too slow, or if the mat is too wet; on the other hand if the mat is too dry or the pressure of the dandy too light then the mark is indistinct.

Certain other aspects of watermarking require special consideration. In the first place a watermarking dandy is generally more likely to create trouble with picking and bubbles at the places where the marks themselves protrude, especially when using an intricate or heavy design. If this cannot be overcome by raising the dandy or by more efficient steam spraying while running, the quality of the mark deteriorates and frequent stoppage of the dandy for cleaning will be necessary.

The type of furnish and beating also has an important bearing on the quality of a watermark and in general shorter fibres such as those produced in well-beaten esparto yield the best results. Loadings, to a certain extent, are also beneficial. What seems to be required is a reasonable proportion of fine fibres or particles which can be compressed through the upper layers of the fibre mat by the watermark to a greater extent than by the remainder of the dandy mesh, thereby creating an optical difference in reflectivity through the sheet.

Watermarking to register requires precise matching of the dandy and wire speeds coupled with careful control of shrinkage of the sheet in both directions. The first requirement is achieved automatically on slower machines provided adequate pressure of the dandy on the wire can be

obtained and the frictional resistance to rotation is kept low. On faster machines it becomes more imperative to have a dandy drive and a measurement of the differential speed.

Controlling shrinkage is a more difficult matter, depending as it does on so many factors such as wetness of the stock, the tightness of the draws and felts, and the general characteristics of the sheet. In the long run better control all through the stock preparation and machine, and repeatability of operation from one making to the next, are the only means of obtaining a satisfactory register with reasonable speed and accuracy. Otherwise if the register becomes too narrow in the machine direction it is necessary to tighten draws, free the stock, or slow the dandy either by altering the drive speed, lifting the dandy slightly, or, if neither of these are possible, the edges of a dandy free-running on the wire can be built up. If register becomes too narrow in the cross direction, tightening the dry felts will usually reduce cross-direction shrinkage; slackening the draws will also help though this, of course, is also liable to affect the machine-direction register to a certain degree. Excessive fibre alignment in the machine direction increases cross-direction shrinkage and it may be possible to effect an alteration to this. Lack of uniformity of watermark across the sheet is, however, more commonly associated with the differential shrinkage caused by a general unevenness in cross-machine substance and moisture at the reel-up, which requires a more extensive investigation to remedy.

3B.6 COUCHING

There are three principal methods for couching the web from the paper machine wire: the jacketed top couch and plain bottom roll, the suction couch usually with presser roll, and the plain or suction felt transfer. Each method has its own variations and refinements and these will now be described in turn.

3B.6 1 Jacket couch

The jacketed top couch is the oldest type and derives directly from the practice in hand-made paper of couching by pressure on to a piece of dampened felt. The normal operation involves running the jacket roll slightly set back above a solid or grooved brass or rubber covered wire roll, which is generally also the drive roll. The top roll exerts a slight pressure on the wire and this serves the dual purpose of removing some water from the sheet and, more important from the point of view of couching, provides the essential water film between the wire and the fibre mat. Some water passes through the wire and escapes down the wire roll, similar to a plain press nip, but probably the majority enters the jacket to be squeezed out at the squeeze roll or guard board.

Once the sheet has passed under the jacket it is important for ease of couching to remove it from the wire as soon as possible. The longer the sheet remains on the wire the more water is reabsorbed from the wire mesh and the greater becomes the adhesive force which it is necessary to

overcome. The usual configuration with this type of couch results in the sheet being drawn from the wire well down the drive roll; the position of the jacket roll prevents couching the sheet too close to the jacket nip except with a very tight draw and this is undesirable for many reasons discussed earlier. It is suggested that Fig. 3.14 shows the most preferable arrangement permitting early take-off at a reasonably high angle. In this, both the lead roll and first press felt roll are higher than normal; adjustment of the former serves the purpose of guiding the path of the web to enable
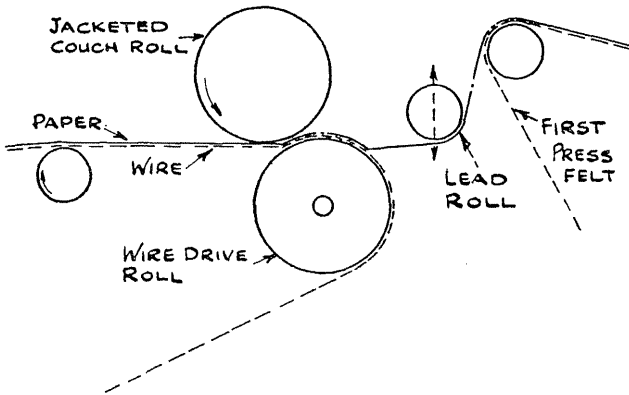
Fig. 3.14. Preferable arrangement of open draw with a jacketed top couch roll

the take-off point to be as close as possible to the jacket nip with the draw slackened back during running as far as seems advisable. Transfer of the tail at the speeds associated with this type of couch would normally be by hand, possibly with the aid of a lump of wet broke.

The most difficult feature of this type of couch is the operation of the jacketed top roll. The load exerted by the roll must be light, otherwise crushing will occur and the wire, which is only partly supported underneath, may be subjected to strain; for these reasons a large roll is preferable as this spreads the load and reduces the pressure on the mat and wire. Nevertheless the wire usually has to drive the top roll so sufficient pressure is necessary for this purpose; to assist in this end roll bearings have to be kept as free as possible but even then at higher speeds running the roll in this way without crushing becomes difficult. A grooved bottom couch roll, which makes removal of the expressed water easier, is one way of helping to prevent crushing but this has other disadvantages. A table roll is always necessary between the suction boxes and the top roll so that the wire does not rub on the trailing edge of the last box.

A guard board is frequently used on top of the jacket to squeeze out water and conduct it to the side of the machine, but this can cause undue wear on the jacket and produce a heavy breaking force on the undriven

top roll; also it is not easy to adjust pressure on the ends to keep the jacket level. For these reasons the board is commonly replaced, particularly nowadays on faster machines, by a rubber squeeze roll. This roll serves the same purpose but has a gentler action; also a greater pressure is possible than with a guard board so that more water can be removed before a point is reached where the jacket tends to loosen and ruckle up into creases. The roll requires a certain amount of camber to offset the pressure applied and a doctor to keep the surface clean. Occasionally an emergency board is still used in front of the squeeze roll; it is placed just clear of the jacket but may be quickly lowered if the sheet goes up the jacket—it is not a guard board and only serves the function of saving the jacket from being spoilt by the sheet being pressed into it at the squeeze roll.

Keeping the jacket in satisfactory condition can be a problem, especially where it tends to pick up fibre from the deckle edges. A spray could be necessary to prevent this but even so the jacket becomes plugged eventually and the nap gets worn. When this occurs the sheet will tend to leave the wire and follow the jacket, making it necessary to stop the machine to clean the jacket and (though some do not recommend this) rub up the nap with teezers. These difficulties become greater at higher speeds, of course, and the substitution of a rubber presser roll may be required. But this reduces appreciably the water removed and is normally associated with a suction couch.

3B.6 2. Suction couch roll

According to Hendry (19) the original invention of the suction couch was intended as a replacement of suction boxes to minimize friction on the wire, but for some unknown reason it was first substituted for the couch. This apparently fortuitous application has had far-reaching effects for there is no doubt that the suction couch has many advantages over the plain jacket couch, especially on fast machines. There is good evidence to indicate that it removes more water but possibly the main advantage is the reduction of accidents to the wire and the avoidance of trouble with jackets. The suction couch roll is frequently also the drive and turning roll for the wire which has the added advantage compared to a solid roll that the suction helps to reduce slip of the wire. However, it is becoming more usual on faster machines to have a forward roll to provide all or most of the drive requirements. On machines with a felt transfer from the wire, the forward roll is in general use anyway.

In operation the vacuum in the suction box, aided in most cases by a presser roll, draws water into the couch holes; after passing the trailing seal-strip, air entering the holes from the inside throws the water outwards, to be largely contained by the wire then thrown out subsequently by centrifugal force at the point where the wire leaves the roll. This throw-out is not usually troublesome though occasionally when the wire follows well round the roll a deflector plate may be required to prevent the spray hitting the underpart of the wire and carrying into the couch nip. A light rubber doctor can also be helpful for reducing the volume of water carried round

on the roll surface into the nip. On most machines it is unlikely that much water is drawn through the holes into the vacuum pump.

Once the sheet has passed over the suction area reabsorption of water from the wire will begin immediately, reducing the solids content of the web and increasing adhesion to the wire. As with the jacket couch, therefore, it is important to remove the sheet from the wire as early as possible, though in this case a compromise must be reached to reduce the appearance of shadow-marking which, as described in greater detail in 3A.42, diminishes in intensity as water is reabsorbed. The rate of reabsorption and reduction of shadow-mark must be primarily a function of the web porosity; where shadow-marking cannot be removed satisfactorily by
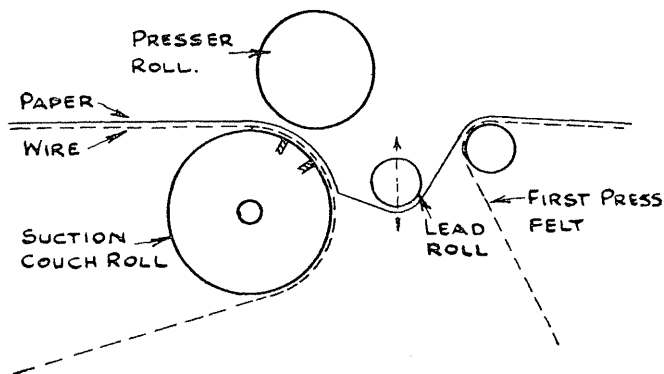
Fig. 3.15. Preferable arrangement of suction couch and pressure roll with an open draw

permitting the web to remain longer on the wire, removal of the presser roll and reduction of the vacuum in the couch both help though at the expense of reduced water removal at the suction couch.

When the shadow-marking problem is under control and it is possible to effect earlier removal from the wire, then it is not necessary to alter the usual couching geometry by raising the lead and felt rolls as in the case of the jacket couch. Instead the suction box may simply be moved round the roll until the angle between the trailing seal and the take-off point is brought to the minimum tolerable for shadow-marking; even with a reasonably high angle of take-off this angle should normally be sufficient not to cause any problem in positioning the presser roll, nor in blowing the tail over during feeding up, see Fig. 3.15. The position of the lead roll close to the couch is important to prevent excessive movement of the take-off line; if the draw were tightened sufficiently for this line to fall back to the suction box zone, picking occurs due to the uneven pull on hole and land areas.

When driving the wire section the suction couch roll is made relatively large in diameter to reduce the speed of rotation and the radius of turn of the wire round the roll, both of which contribute to keeping down the

degree of slippage of the wire relative to the roll and affect wear on the wire, as will be discussed in **3B.7 1**. Holes are countersunk to help apply the vacuum as evenly as possible to the sheet and pitched to maintain the hole area over the suction box as constant as possible during rotation, thereby reducing the possibility of vacuum oscillations. A fresh-water spray inside the roll should be of the high-pressure, low-volume type, preferably oscillating, and set carefully to give even application across the length of the roll; the function and operation of the spray is essentially similar to those used in suction presses and the precautions necessary for efficient use are fully dealt with in the section devoted to that subject. This applies also to setting of the edge deckle and maintenance of the suction box seals.

Some suction couches are equipped with a double box; the first compartment is wide and under a relatively low vacuum (10 in. Hg.), having the object of removing air from the couch holes and sealing the sheet; the second compartment is the same as the normal box though rather narrower. No data has been made available on the relative benefits of this design though prior evacuation of the holes, because of their high volume, may well lead to power savings depending on the arrangement of vacuum equipment on the machine.

The function of the presser or lump-breaker roll is to close up the sheet at the suction couch and raise the vacuum to improve the dewatering action. This increases the wet-web strength at the couch and is also generally reported to reduce draw variations. Particularly when a dandy is not in use the presser roll is also thought to reduce the frequency of breaks at the couch by removing lumps in the web and reducing picking. The roll is usually situated either over the leading seal of the suction box or, with a double box, over the middle of the first compartment.

Although the presser roll is undoubtedly advantageous it must be recognized that smooth operation may not always be easy to attain. The rubber should be soft (200–250 P. & J.) and pressure of the roll on the wire, allied to a suitable camber, requires careful setting; if the roll does not extend over the trim (a precaution sometimes adopted to prevent build-up of fibre on the roll at the deckle edges) then ridges in the wire may gradually appear opposite the ends of the roll. To keep the roll clean it is always necessary to have a fine spray skimming the surface on the up-going side and this is preferably of warm fresh water. If this spray is allowed to become uneven in application moisture variations across the web are observable, and if the volume of water becomes too great the whole value of the presser roll in improving dewatering at the couch may be lost.

On faster machines it may be found necessary to equip the presser roll with a separate drive either for lowering the roll at an adequate speed or for satisfactory continuous running. Particularly under such circumstances, as also on the many machines normally running with a presser roll which is very troublesome to operate due to fibre picking or repeated damage to the wire, it may well be found that lifting the roll only reduces the vacuum on the couch by 2 in. or 3 in. Hg. and this may have little effect on the moisture of the web, at least after the presses. Provided the frequency of

breaks at the couch were effectively unaltered there would in this case be a strong argument for removing the roll altogether.

3B.6 3 Operating the suction couch

The suction couch assists in the action of couching by providing a film of water between the sheet and the wire, though the occurrence of shadow-marking reduces its efficiency in this respect; before the sheet can be removed some reabsorption of water back into the sheet must be permitted in order to equalize the moisture. For this reason the whole value of the suction couch has at times been questioned. In particular, Baggallay (17) has reported that he placed a small suction box in front of the suction couch of a medium-speed machine and, by moving forward the lead roll over the wire, arranged to remove the web from the wire at that position; the solids content of the web showed no reduction despite the fact that the suction couch was then not in use. This finding has lead to development of the 'Baggallay box' as a cheap and simple couching device which can sometimes with advantage replace a difficult jacket couch arrangement. The box normally consists of a single compartment to which a vacuum of 5 to 10 in. Hg. is applied, together with a blowing compartment or jet to assist in getting the sheet up when feeding the tail through. In operation the web leaves the wire just at the trailing side of the suction slot and the open draw to the lead roll must be kept as short as possible by placing the roll just above the box.

On the other hand Macdonald *et al.* (49) have reported data from one machine where the suction couch appears to act as a stabilizing influence on the solids content of the web at the couch; lowering the vacuum in the suction boxes only resulted in the suction couch extracting a greater quantity of water with no significant change in the solids content entering the presses. Even if this applies only partially to other machines it could well represent a valuable means of reducing power consumption and wire wear, particularly since any small decrease in dryness at the couch is partly compensated for in the presses.

The only systematic investigation of the dewatering action of the suction couch appearing in the literature is due to Brauns and Oskarsson (5). These workers used an experimental machine and a couch in which the width of the suction box could be varied, as well as the vacuum applied. In addition the air flowing through the box was varied, with other conditions constant, by means of a plastic cloth which could be pressed on to the web above a portion of the suction box. Unbleached kraft pulp at two degrees of wetness was used and in all the experiments the solids content of the sheet before the suction couch remained constant.

The results of this work indicate that for a given vacuum and air flow per unit area, the width of the suction box (or the time vacuum applied to the sheet) has little effect on the dryness, giving only a very slight improvement with increasing width. The vacuum applied, as expected, has a much greater influence on the dryness, see Fig. 3.16a, and the relationship appears to be approximately linear. The graph is transposed in Fig.
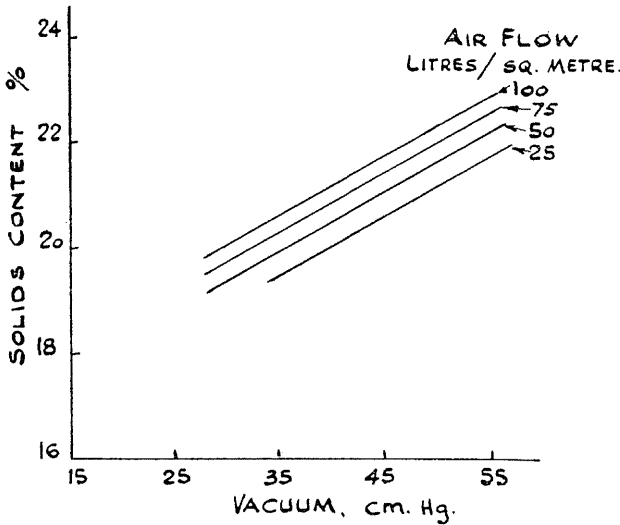
Fig. 3.16a. Relation between solids content of web and vacuum applied to a suction couch with different air flows through the sheet (after Brauns and Oskarsson)
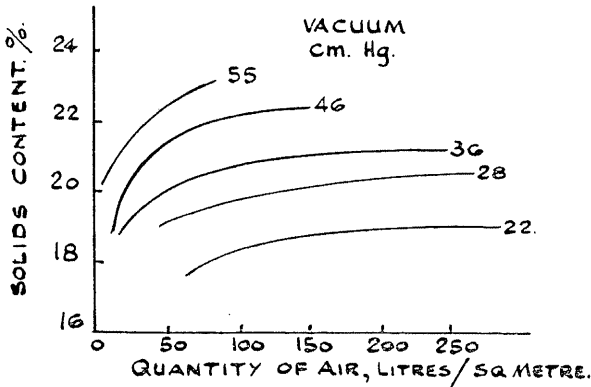

Fig. 3.16b. The results of Fig. 16a transposed to illustrate the effect of air flow on dryness of the sheet with vacuum constant.

3.16b and shows there that when a greater volume of air is passed through the sheet for a given vacuum and suction area, i.e. when the velocity is greater, then this also produces an improvement in the dryness; however, the effect diminishes for higher volumes and beyond a certain quantity of air the dryness is only imperceptibly improved.

The implication of these results is that dewatering at the suction couch is closely dependent on the pull exerted within the sheet, presumably because this governs the smallness of the capillaries which may be evacuated. In contrast to the suction boxes, at least in the early 'wet' positions, which depend for removal of water mainly on the scraping action of the wire on the box, at the suction couch the passage of air through the sheet contributes relatively more to the effectiveness of the operation. In this respect dewatering is dependent on the use of air as a medium for transportation of the water droplets extracted and, to a lesser extent, for evaporation into vapour form.

From this work it is clear that suction boxes could profitably be narrower in width on many machines. A smaller box has little effect in so far as it diminishes the time of application of vacuum, but it will certainly decrease the volume of air passing through the sheet; the effect of this on the dryness will be of slight value unless the quantity of air becomes comparatively small, but the power consumption will decrease approximately pro rata with the air volume.

The vacuum has the most effect on the dryness of the sheet so that the use of a presser roll to increase it by compacting the web should normally be justified. With a fixed-performance vacuum pump a further advantage to narrowing the width of the suction box is that, by reducing the volume of air removed, a beneficial increase in vacuum will be brought about, though in this connection it is important to realize that the holes themselves carry round an appreciable volume of air that must be evacuated. This vacuum increase alone can be expected to improve the dewatering efficiency so there seems to be a good case for constructing the normal suction box to make an alteration in width practicable during operation; to avoid interference with the take-off conditions it would be preferable to achieve this by making the leading seal adjustable, not a difficult engineering operation and one which could well permit an optimum working position to be found for any particular set of conditions.

3B.6 4. Felt transfer

With increasing machine speeds a point is reached where operation of the open draw becomes uneconomical—the reasons for this have already been considered in some detail. The avoidance of an open-draw by using a felt to transfer the sheet from the wire, either directly ('lick-up') or with the aid of a suction roll ('pick-up'), has therefore many advantages. The success of this method of transfer to the presses depends on ensuring that the felt presents a greater adhesion to the top of the sheet than the wire does to the underside of the sheet. With a lick-up this necessitates arranging for the face side of the felt to be extremely dense and also ensuring that a film of water is present on the surface by using a full-width shower on the felt. For suction pick-up a relatively open felt is necessary to allow the influence of the suction to be exerted, though at the same time the face side of the felt must be sufficiently closely woven to stick easily to the web. Both types

are generally used in conjunction with a forward-drive roll, the transfer line lying between this roll and the couch.

Considering first the actual couching operation it is particularly important, especially when operating this form of transfer close to the maximum substance possible under the particular machine conditions, to ensure that adhesion of the sheet to the wire is at a minimum. On many machines the pick-up line is, for felt and wire changing convenience, placed much closer to the forward drive roll than the suction couch roll; this gives the web a much longer time to reabsorb water from the wire, decreasing the solids content and increasing the adhesion, a process which is all the more rapid since the wire separates from the couch roll and is, therefore, able to release water much easier. Hendry (3) has confirmed that maximum water removal occurs when the suction boxes in the pick-up roll and couch roll are practically aligned and, as Baggallay (17) observed, if couching is delayed too long after the web has passed over the suction couch roll then the results can be visible in the amount of fibre left adhering to the wire. If it is not practicable, for engineering or shadow-marking considerations, to position the transfer roll close up to the suction couch roll, then much benefit is gained by using a small suction box immediately before the pick-up line.

A separate drive for a suction pick-up roll is necessary, though not usually for a straightforward lick-up roll. Frequently with this sort of arrangement, at least on faster machines, the couch roll is driven in addition to the forward roll, and sometimes the first wire return roll may also be driven. The trailing seal-strip in the suction couch roll should for preference be wide; this increases the angle through which the roll turns before vacuum in the holes is released to throw out a spray of water which must not, of course, splash the wire or forward drive roll.

Pressure of the transfer roll on the wire requires careful setting to avoid crushing the sheet or damaging the wire. When feeding up it is more usual to raise the wire by moving the forward drive roll than to lower the transfer roll, except possibly with a plain lick-up roll. A slight positive draw is usually applied as this is found to prevent creasing or a tendency for the paper to crêpe in the nip. With a suction pick-up the deckles are set in the roll to leave the trim on the wire; with a lick-up the trim is either blown off the wire before the couch or taken up with the main part of the sheet and removed from the lick-up felt by rollers or by some other means. The edges of the felt in a pick-up arrangement are apt to get dirty and a shift in deckle can create a problem in preventing the trim following the felt. The special requirements of these two basic methods will now be discussed in greater detail.

3B.6 5 Couching with a lick-up arrangement

The type of transfer involving a straightforward lick-up felt is of limited use and, in fact, is applied exclusively to extremely light-weight papers. Any attempt to lick-up heavier papers involves having the felt so damp, and the paper so dry, as to be uneconomical and operationally hazardous. It is essential to keep adhesion to the wire to a minimum; the lick-up roll

is therefore situated above the couch roll which, for this grade of paper, is either plain, or grooved to enable air to enter under the web immediately after the nip formed by the lick-up roll.

A further difficulty with the lick-up arrangement is removal of the sheet from the felt itself. It is impossible to transfer to another felt, because the lick-up felt is so dense and damp, so the sheet must be taken through the press section on the lick-up felt and eventually transferred on to either an M.G. or a small-diameter pony cylinder. This requires the assistance of a roll giving quite a heavy pressure on to the cylinder and makes the whole pressing operation a relatively inefficient process. Further, the large volume of water in the felt makes crushing difficult to avoid. Even so, provided the felt can be kept with an adequate 'skin' on the surface, for light papers this method offers some advantages.

Dixon (32) has reported comparative figures taken from two machines making the same grade of tissue from the same furnish, one with a lick-up arrangement and the other with a suction pick-up. He cites the advantages of the former as follows: less felt marking of the sheet due to the closer weave of the lick-up felt, longer felt life if it is kept properly cleaned (though the felt is more expensive), and lower power requirements. Against this the pick-up arrangement, being more efficient in the presses and in this case extracting twice as much water for the same loading, yields a higher dryness entering the drying section; also transfer from the pick-up felt is easier, as is cleaning of the felt because it is much more open and runs comparatively dry.

3B.6 6 Suction pick-up

It is generally considered that use of a conventional suction pick-up arrangement and transfer to a second felt at the first press nip has no advantages from the point of view of water removal. Burnett (25), for example, found that little water was extracted at either the pick-up or transfer nips on a typical machine, conditions at both being governed primarily by the necessity of transferring the sheet. The main advantage gained by this arrangement is undoubtedly safe transport of the web.

Because of the relatively heavy quantitities of water sucked through the pick-up felt it tends to get dirty quickly unless efficient cleaning devices are used. This applies especially to the face side which, if allowed to get dirty, marks the sheet and can create a problem by throwing fibre clumps on to the wire as the felt drops down to the pick-up roll. Dixon (32) gives details of using a variety of pick-up felts, many with synthetic content, and emphasizes the importance of matching this felt with the felt on to which the paper is subsequently transferred. The outcome of many trials in this particular case was adoption of a high terylene content pick-up felt which does not reduce in thickness throughout its life and is usually removed when marking becomes excessive.

Jordansson (27) has reported experimental work on a pick-up arrangement and amongst other things demonstrated that an upper substance of sheet exists beyond which transfer by this means becomes unreliable and

the paper is liable to drop off the felt. The point when this is reached will depend on many factors, including the dryness and constitution (particularly porosity) of the web, openness of the felt, etc.; in this work substances of 150 g.s.m. never caused any trouble, while at 200 g.s.m. a critical stage was being approached. Placing a felt suction box between the pick-up roll and transfer press made the operation more reliable at this heavier substance, especially if the pick-up felt were dampened with a spray before meeting the sheet. It was also found useful to make the sheet as dry as possible at the pick-up line since this reduces the weight to be carried. However, modern installations combine the pick-up roll and transfer press, and with this arrangement the paper can be held to the felt simply by applying suction right round the roll (see Part 4).

Another way of overcoming this problem has been proposed by Kitano (36); this involves using air pressure to lift the sheet on to a 'post-up' roll, which is a wire net cylinder of fairly small diameter, and thence to a felt. A rather complicated set of air seals is needed but it is claimed that speeds up to 2,000 f.p.m. have been achieved without transfer difficulties by this means.

When feeding up the sheet it is useful if the vacuum in the pick-up roll can be temporarily increased. Under normal operation the vacuum is kept as low as is necessary for safe transfer (5 to 10 in. Hg.), otherwise water drawn into the holes can be troublesome to remove without splashing. Dixon (2) has discussed the problems involved in this with regard to a stack press which presents precisely the same problem at the pick-up roll; further discussion is conveniently left to section **4B.3 6** et seq. on the presses which deals with this.

3B.7 THE WIRE AND SHOWERS

The wire is, of course, an essential part of the Fourdrinier machine process, acting as a convenient means of transporting the web while drainage occurs and the sheet is formed; however, the direct influence of the wire on the paper is, by and large, confined to the size of the mesh. A fine mesh gives a greater fibre and loading retention and less wire mark, but a slower drainage. In practice the best compromise is governed to a large extent by the substance range run on the machine: coarse (55 × 50) for board and kraft wrapper; average (64 × 52) for newsprint and printing papers; slightly finer (70 × 60) for ordinary tissues and writing papers where loading retention may be more important; and very fine (100 × 80) for thin cigarette and condenser tissues. Apart from this aspect the main problem with any wire is to prevent an excessive rate of wear and retain the same drainage conditions through the life of the wire.

3B.7 1 Wire wear

If run long enough and kept free from damage, the vast majority of machine wires eventually have to be changed because of holes in the body of the wire and cracks appearing at the edges. These may be caused directly by mechanical faults, but they may equally represent the weakest link in a

wire which has been worn down to the point where the slightest damage or misalignment will show itself. Much attention has been given to this whole problem in recent years, with particular reference to faster machines where wire life may become reduced to a few days, and this will now be summarized. Paton (7), Boadway (42), Macdonald *et al.* (49), Friese (54), Johnson and Gavelin (77), Lawson and Lambert (78), Redfern and Gavelin (92), and Reynolds (93) are the main contributors from which this summary is drawn.

During the life of a wire the inside knuckles are worn and the thickness of the wire diminishes. The rate of wear is greater at the beginning of the wire's life because the smaller area of contact creates a higher pressure and, therefore, a greater abrasion rate of the wire. Most wear occurs at the suction boxes, as discussed in 3B.4 1 et seq. in some detail; slip at the driving roll and at other rolls, though probably small (Macdonald found
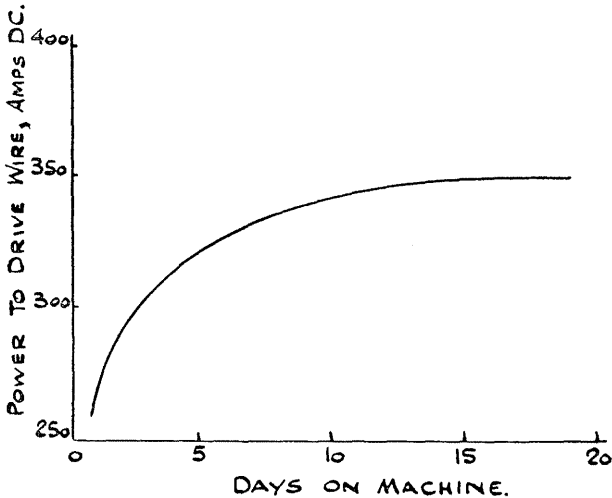
Fig. 3.17. Increase in power required to drive wire during its life on the machine

no case where a difference greater than 0·5 ft./min. occurred on fast machines exceeding 1,200 ft./min. in speed), can also be expected to contribute to wear, particularly if bearings are stiff or doctors too hard on. As the area of contact increases, the total drag on the wire is also raised producing an increase in the power consumed by the wire drive, see Fig. 3.17. Normal wear of the under-surface of the wire will cause the knuckles to become smooth and polished; if they are scored or scratched this is due to the action of abrasive particles and it has been shown that the rate of wear is then on average much greater.

When the drive roll is a suction couch it has been found that the initial rate of wear of the wire is greater. Some creep round the drive roll is

unavoidable because of the slight shrinkage of the wire which occurs with decrease in tension from the pulling to the return side of the roll; this wears the wire at a rate which is higher when the open area of the couch is greater. Wear also appears to be influenced by the extent to which the wire is driven by the vacuum in the suction box; if the greater part of the change in tension of the wire round the roll occurs within the width of the box, then the higher pressure between the wire and roll in that region produces greater friction on the wire as slippage occurs. For these reasons, on faster machines it appears more important to reduce or eliminate the wire driving force exerted by a suction couch in favour of using a separate solid driving roll; over this forward drive roll, wire wear will be less due to the lower pressure of the wire on the solid surface and the avoidance of additional abrasive action produced by the wire knuckles rubbing over the couch holes. With this arrangement some drive to the suction couch is still preferable to overcome friction at the box seals and bearings, otherwise some slip will occur and the wire will be worn there anyway. To ensure there is little wire creep in the suction zone it is advised that the wire laps at least 10 deg. on either side of the box.

With increasing machine speeds the wire needs to be run at a higher tension to prevent slipping at the drive roll; if this occurs it causes the load to drop spasmodically and the draws oscillate. Greater tension may also be necessary to reduce stock jump at the table rolls. When a suction couch is used as the drive roll it has been shown that higher tensions create greater wire wear due to the greater creep round the roll occasioned by the bigger difference in tension at the pulling and return side. In this case a forward drive roll becomes even more essential and automatic control of the tension by one or other of the devices available is also desirable.

3B.7 2 Damage to the wire

Although steady wear is the most common cause for removal of wires, they are, of course, particularly vulnerable to accidental damage, especially when being put on the machine, and no machineman needs to be warned that great care and close observation of the wire are needed during running. The various parts of the section which contact the wire should be kept in good mechanical condition to prevent the appearance of ridges particularly when running tension is high: thus, rolls need to be well balanced; forming board, baffle, and suction box surfaces smooth; presser roll pressure not excessive; jets from the wire showers uniform (especially if the water is at a different temperature to the wire at start-up); and so forth. Any unevenness of tension across the machine may cause stretching early on in the life of the wire which gives trouble if tension is slackened off later on. Also stiffness in wire guide spades or undue tightness at the edges subject the wire to greater stress in this region and increase the likelihood that cracks appear; it has been suggested that the edges of new wires should be deliberately stretched to reduce the possibility of cracks appearing, but a more common palliative is to use plastic edges.

A small hard particle passing between the wire and a roll creates a pimple

which wears faster than surrounding portions of the wire, especially when facing inwards, so that sooner or later a burst occurs. Inward indentations are frequently caused at the first wire return roll and the incidence of damage from this has been shown to be higher for faster machines (where wire tension is usually greater); other factors likely to increase the frequency of this type of damage are finer mesh wires, a wide wrap round the roll, and a small diameter return roll. Outward indentations are not so serious but a bad pimple can eventually lead to a crack across the wire.

In some mills corrosion of wires presents a more serious problem than either wear or damage due to other causes. Studies of this have been made by analyzing stock and whitewater systems and it appears that in some cases a greater loss of copper can take place from over the whole body of the wire than is lost at the knuckles due to normal wear. Provided the loss is fairly uniform over the whole surface area of the wire the strength is not unduly affected but it is more usual for attack not to be uniform and concentrations cause pits in the wire which severely weaken it. Corrosion increases with a lower pH but also depends on many other factors; addition to the stock or showers of an inhibitor, or putting a suitable coating on the wire, are reported to help but economically the best solution to the problem in the long-run is likely to be the use of plastic wire.

3B.7 3 Cleaning the wire

It is most important to keep the wire scrupulously clean both to prevent the mesh gradually becoming clogged and to reduce the possibility of damage. As most damage to a wire occurs when clumps of fibre pass between the wire and the first return roll the most important cleaning shower is situated between the couch and this roll. To do an efficient job all trace of fibre adhering to the wire on the return run should be eliminated and this task will, of course, be made easier if the sheet has been cleanly couched. With efficient cleaning and the use of trays to prevent backwater from table rolls cascading through the wire underneath, it has become rare for wires to give drainage difficulties due to plugging. But damage of the wire stemming from an indentation caused at the first return roll is not so uncommon.

There is some difference of opinion regarding whether fresh water or whitewater should be used for wire cleaning showers. The adherents of fresh water claim that the use of whitewater damages the wire and is particularly dangerous if the wire is stopped without showers being immediately turned off. There is also doubt cast on the ability of whitewater showers to do an efficient job of cleaning. But using fresh water, unless it be kept separate from the rest of the backwater system and partially recirculated, can be very detrimental to general running stability and it is probably the case these days that most machines, certainly faster ones, are changing over to using whitewater.

With whitewater cleaning showers the lower the consistency, the less likely it is that the wire is damaged or plugged at an emergency stop. For this reason on modern systems whitewater that has passed either through

two save-alls in series or is from the clear section of a disc filter, and is consequently highly clarified, is generally used. This, coupled with the use of high pressures and dual showers close to the couch, gives an efficient means of thoroughly cleaning the wire. Even so, especially when fibre is in the shower system it is important to ensure that plugging does not occur, as nothing is more likely to spoil a wire and give uneven drainage than a gradual fibre build-up in the mesh at one or more places across the machine. For this reason oscillating and self-cleaning showers of various designs are becoming more familiar on machines; some of these are of the automatic purging type while others require manual operation of the cleaning action. Regular inspection for scale and other deposits, together with periodic measurement of the flow to the showers, are highly advisable.

Such showers alone are not usually sufficient to deal with the whole web when this is carried round the couch during a break. In this case it is essential to have a separate powerful knock-off shower that sprays out comparatively large volumes of whitewater. The arrangement of whitewater systems to provide this facility has already been touched upon and one of the problems involved is arranging to start the shower sufficiently quickly when the sheet breaks. With open-draw machines such showers when needed usually have to be kept on all the time and provision made for adequate recirculation. On pick-up machines more warning is available and the turning on of a knock-off shower can be connected to work automatically with movement of the forward-drive roll or other mechanism which governs operation of the pick-up.

There appears to be no generally recognized system of positioning showers for knocking off the sheet at a break. In most cases a first shower inside the wire loosens the sheet and a second more powerful one blows it off; care must be taken here that the trajectory of the sheet as it falls from the wire does not foul the first return roll. On some machines a single shower loosens the sheet which is then transferred to the first return roll and doctored off; in this case with the sheet passing between the wire and return roll there is greater danger of damaging the wire and an excellent doctor on the roll is essential for success.

The only systematic investigation into the action of wire cleaning sprays known to the author has been due to Brecht and Weitzel (63). The efficiency of various models of circular and flat jet sprays was evaluated and the conclusion reached that the flat jet gives the better cleaning action for a given amount of water; however, flat jet sprays have a tendency to vary considerably in cleaning efficiency across their width and careful design is required. With all types the most efficient cleaning action occurs when the jet impinges vertically on the wire.

3B.7 4 Wire material

The use of non-ferrous metal wires was universal up to a few years ago and the development of suitable metals to give the necessary ductility and strength, together with abrasion and fatigue resistance, has been described by several authors (notably Paton (7)). Twill weave wires have been shown

to have a greater tensile strength than plain wires for a given reduction in their thickness due to wear, and this is of great importance to the wire life. The wire seam rarely gives any trouble on the machine though the occasional wire does give way first at the seam. At one time the seam was especially prone to becoming plugged with fibre and other deposits but modern techniques of welding have eliminated this problem. It is also usual for the end of one wire to be joined to a different wire two or three positions away; this gives added protection against the possibility of grooving the suction boxes.

The primary disadvantage of metal wires is their relatively short life. Plastic wires or fabrics, though costing substantially more than metal at the present time, can give an appreciably longer running time particularly on machines where corrosion limits the normal wire life. Other advantages are greater ease of cleaning off pitch and other contaminants with steam showers (pitch adheres less in the first place), better retention, and (though opinions differ on this point) less tendency to get made up. Also, because the fabric can be flexed much more than a wire, it is simpler and quicker to put on the machine, particularly where space in the aisle is cramped. Adhesion of the web to a fabric is considered less than to a wire; drainage and wire mark appear to be similar. In comparing the merits of the two materials a full economic appraisal is, of course, necessary and this should take account of wire changing costs and downtime for cleaning and repair; in general it is thought that plastic wires are particularly beneficial on machines which have corrosion or pitch problems, or when the frequency of wire changes represents a substantial total cost.

Plastic wires used to stretch 2 to 3 per cent. during the course of their life and this always required modification of the run of the wire because normally a stretch of only at most a few inches is possible; on slower machines this did not present any real problem but faster machines requiring greater tension needed considerable alteration. For example, Macpherson (66) has described in some detail the experiences on one machine where a change over to plastic wires involved installing three expander rolls and more return rolls to give a larger stretch and an adequate wrap round the expander rolls. However, the problem of excessive stretch has now been overcome so this particular installation cannot be regarded as typical. Some alterations are generally needed to take plastic wires and these include a single expander roll to keep the wire tight across the machine, plastic or stainless steel suction box covers, and the installation of one or two plastic or stainless steel foils to improve drainage where this is likely to produce useful results. Disadvantages mentioned in the use of plastic wires, apart from the greater stretch, are higher risk of being punctured by hard objects, lower strength, and greater liability to wrinkle. The use of a coarser wire to support the finer plastic wire over the suction boxes has been successfully applied as a means of further reducing wear (104).

Reports have also appeared describing the merits of stainless steel and chromium-plated wires, and under certain conditions these appear to improve on the life of ordinary phosphor-bronze wires.

3B.7 5 Slope of the wire

The idea of sloping the wire downwards first arose due to the difficulty in getting a fast enough flow from the old dam-type slice. Also, with the low heads used with this simple type of slice a large difference in velocity can exist between the upper and lower layers of the flow particularly with heavier papers. Sloping the wire, by giving a slight acceleration to the upper layers before they become fixed in the mat, may be expected to reduce this difference.

Upward sloping of the wire is occasionally used on old machines when it is desired to increase the drainage rate by the creation of a deeper stock thickness in the first few feet of drainage; it is stated that faster speeds can then be achieved and an additional advantage often claimed is that the slight deceleration of the upper regions of the stock assists in deflocculation of these layers. Very steeply sloping wires are used in association with pressure formation on special tissue machines and also when strong machine direction alignment of the fibres is desired.

It is sometimes claimed that downward slope on faster machines assists in delaying drainage (by carrying the water further down the wire) and thereby can benefit formation; another idea current is that slope will help to overcome air friction on the upper surface. In the author's opinion neither effect is likely to prove significant in practice. Firstly, drainage rate is unlikely to be altered by the slope because on faster machines the gravitational element is insignificant; effectively all drainage occurs at the table rolls and foils and the forces involved in this are unaffected by the slope. Secondly, any frictional effect of the air on the upper surface of the stock cannot have much chance to affect the velocity significantly because the increasing pull of lower layers as the mat thickens will keep the velocity identical to that of the wire.

There have never been any controlled experiments on the effect of slope and its influence at slower speeds can only be conjectured; however, it is worth pointing out that as a way of altering the drainage it is certainly less flexible compared to other means available because the engineering arrangements effectively require that once decided upon the slope is fixed. A simple calculation shows that moderate degrees of slope cannot have a significant effect on the formation and drainage of the stock over about 1,000 ft./min., so for faster machines whether or not the wire slopes may be settled primarily for convenience of design.

3B.8 BREAST BOX STOCK CONSISTENCY AND TEMPERATURE

The influence of breast box consistency on formation has already been discussed in some detail; in particular, the point has been made that in general under any given machine conditions the lower the consistency (to the point where the flow from the slice becomes so great that instabilities occur), the easier it will be to obtain a satisfactory formation. Wrist (84), for example, demonstrated that the random variation in substance over small areas is significantly less at lower consistencies. In practice the breast

box consistency is governed by the relation between the drainage rate and the position of the dry-line: if drainage rate decreases and the dry-line moves towards the couch, the machineman circulates less backwater which increases the consistency.

It is not possible to define an ideal position for the dry-line which in practice is arrived at by reconciling the conflicting requirements of low breast box stock consistency and high solids content at the couch. A difference in moisture after the suction boxes becomes proportionally lower after the couch, and this in turn becomes proportionately lower after the presses. Thus there is no particular merit in prejudicing formation of the sheet in an attempt to obtain too high a dryness at the couch. But at the same time, of course, the wet strength of the sheet must always be above the point where transfer from the wire becomes hazardous.

A frequent problem is shortage of drainage capacity; this necessitates compromising formation by the need to run the breast box consistency higher than is desirable in an endeavour to obtain a sheet sufficiently dry to withstand couching. On any machine drainage rate can be increased in several ways by modifying the wire table or increasing the water extracted at the suction boxes or couch. These points have been dealt with earlier. Otherwise under any particular running conditions the factor having the greatest influence on drainage rate is the temperature of the stock; an increase of temperature, by lowering the viscosity and surface tension, reduces resistance to flow through the fibrous mat and wire mesh.

It is common practice to heat stock in the main backwater pit and elsewhere purely to gain this advantage in quicker drainage. In integrated mills the stock has already been heated during preparation of the pulp but otherwise some consumption of steam is required for this purpose; in this case it is desirable to make some assessment, however approximate, of the added cost of the steam against the benefits obtained in the form of a lower frequency of downtime or increased speed. Generally such a calculation may be expected to show that the addition of steam is well worthwhile to quite high temperatures but a limit must be imposed by the necessity of keeping working conditions at the wet-end tolerable. A disadvantage of heating the stock, as shown by the work of Burkhard and Wrist mentioned earlier, is that a rise in temperature lowers the machine speed at which the onset of kick-up occurs.

Little data is available to demonstrate the change in drainage rate with temperature under actual machine conditions. Bennett's work indicated that a 4 deg. F. rise in temperature on 35 deg. F. increased the overall drainage rate by approximately 2 per cent., the increase being proportionately greater in the second half of the table.

3B.9 MACHINE SPEED, SUBSTANCE AND STUFF TREATMENT

The influence of machine speed on most aspects of the wire section has already been treated in detail and for discussion of its effect on drainage behaviour, couching, the dandy, and the wire itself, reference may be made to the appropriate section. In-so-far as conditions in the wire section govern

the maximum speed a machine is capable of under given circumstances, the total drainage capacity is the most important feature which is affected by speed.

The problem posed by limited drainage capacity has been dealt with in the preceding section in relation to the effect on breast box stock consistency and the advantages of heating the stock. There are two further factors which closely affect drainage rate; substance and stock treatment (in the broad sense of changing wetness by beating, refining, addition of broke, etc.), and these are now briefly discussed.

There is little information on the direct effect of substance on dewatering in the wire section except that obtained as part of a larger experiment by Jordannson (27) which is discussed in greater detail in the Part dealing with the presses. This work clearly showed that increasing substance reduces dryness at the couch with other factors constant. Common practice indicates that within a fairly wide range drainage capacity is approximately inversely proportional to the substance—in other words an increase in substance generally requires a corresponding decrease in speed of the same proportion, in such a way that the ultimate production remains roughly the same. Because under normal operation conditions some change in speed is customary when altering making substance (unless other factors such as limitations in the drive have some bearing on the matter) it is usually not possible, nor particularly useful, to try to separate the two effects.

The effect of stuff composition and treatment on drainage rate is a central factor in papermaking. Ideally the furnish should be chosen, blended, and treated to produce a paper with the desired physical properties, but in practice a compromise is always necessary to enable a machine to be run economically. The most important factor affecting this compromise is the behaviour of the stock on the wire. Generally speaking the effect of greater stuff treatment or the addition of a higher proportion of a stronger fibre is to produce a sheet with greater strength properties; this is important not only with respect to the final quality of the paper but also because the wet-strength of the web at the couch for a particular dryness is increased. But greater treatment also produces a slower draining stock and ultimately to obtain a dry enough sheet at the couch either speed must be sacrificed or the treatment reduced. This problem is familiar to all papermakers and its characteristics vary from one machine to the next and depend essentially on the qualities of paper manufactured. In particular on machines making a wide range of substance it is not found possible as the substance is increased simply to decrease the machine speed to keep the production pretty well constant; a reduction of treatment gradually assumes greater importance otherwise it becomes impracticable at the heavier substances to dewater the sheet adequately.

The behaviour on the paper machine wire of different furnishes and the effect of varying degrees and types of treatment is complicated by the great change in drainage rate produced by backwater recirculation of fines and loading, in other words by the question of retention. Laboratory simulation of machine recirculation conditions has only been approached in a rudi-

mentary manner and what knowledge is available on the drainage charac-
teristics of different fibres under actual operating conditions is largely
derived from common observation. Some fibres, such as those from
mechanical pulp, or fines produced essentially by cutting rather than
fibrillating, appear to reduce the drainage rate at the table rolls but have,
if anything, the opposite effect at the suction boxes, (Bennett (9), for
example, found a change of breast box stock C.S.F. had a greater propor-
tional effect on drainage at the earlier table rolls). In a similar way, wet and
dry broke usually exhibits a different effect on the wire. Such phenomena
can be presumed to depend on the relative flexibility of fibres and compac-
tion of the mat at different stages down the wire, and explanations can only
be preferred in general terms.

Apart from its effect on drainage rate, stuff treatment also alters the
porosity of the sheet and this produces a change in the vacuum that is
sustained at suction boxes under the wire and in suction rolls. This change
is a familiar phenomenon and, so long as it can reasonably be isolated from
other factors that also influence porosity such as substance, sheet dryness,
general formation, dandy and presser roll operation, etc., is useful to the
machineman as a guide to changes in composition and treatment of the
fresh stuff. Again, however, such changes must be individual to the machine
and always require interpretation in the light of prevailing operating con-
ditions. Jordansson reported some observations on the effect of beating
an unbleached sulphate pulp with other conditions relatively steady;
dryness at the couch and particularly at the presses reduced (details are
given in section 4B.7) and it is interesting to note that the effect of a change
from 19 deg. S.R. to 66 deg. S.R. was to increase the vacuum at the couch
from 10 in. Hg. to 20 in. Hg., and at the pick-up roll from 10 in. Hg. to
14 in. Hg.

3B.10 EQUIPMENT

To conclude this chapter dealing with operating factors affecting perform-
ance of the wire part, it is appropriate to make a few remarks on some
other pieces of equipment commonly in use that have not so far been
mentioned. These include return rolls and their doctors, the breast roll,
trays, steam sprays, wire stretch and tension devices, wire guides, deckles,
aprons, and cutters.

3B.10 1. Rolls and doctors

All return rolls under a wire require as careful attention in regard to
balancing and positioning as table rolls; in the same way also they require
frequent attention to the journal bearings to ensure that drag on the wire is
kept to a minimum. Doctors are not generally considered necessary on
inside rolls except for machines which do not tray all the table roll back-
water; in the latter case the shower of water falling on to the return run
of the wire saturates the inside rolls and makes a doctor and collecting tray
essential. A doctor is always used on the first outside roll and in this position

is of critical importance in reducing the possibility of damage to the wire caused by lumps of stock failing to be washed off and adhering to the roll.

The angle the doctor makes to the roll it contacts is important: too flat an angle reduces the effect of the doctor and makes it easier for lumps of fibre to pass under when there is a small discrepancy in the evenness of contact; too steep an angle lessens the scraping effect and in excess results in blades chattering. The angle generally recommended is between 25 and 35 deg. and attention is required to ensure that as wear takes place the angle does not exceed the upper figure. Important also is the pressure of the doctor on the roll and to avoid the necessity of heavy pressures to overcome unevenness of contact it is beneficial to construct with light material and use flexible plastic blades. Air-loaded doctors are becoming increasingly common because the facility of being able to vary pressure to suit conditions has been found to be a useful one; the type which allows equal pressure to be exerted all along the doctor, though more expensive than the type which simply loads the ends, is obviously more likely to do an efficient job. Setting the doctor load is largely a matter of trial and error but excessive weight is unwise for this results in a greater drag on the wire particularly when the angle of wrap is small; in some cases it may even then become necessary to apply a separate drive to the roll. As for all doctors, oscillation from side to side geared to the roll rotation is a simple but wise precaution against scoring.

The breast roll doctor is also highly important; without it fibre lumps passsing under the doctor would be squeezed under the wire during its long and tight wrap round the breast roll and eventually mark the wire. Fortunately the consistency of backwater discharged down the roll is low so the risk of marking the wire from this source is much smaller than at the first return roll. A more frequent source of trouble from a poorly-fitting breast roll doctor occurs when an uneven quantity of water is carried round the roll. This is often a source of aeration in the form of relatively large bubbles of air visible on the mat surface and can be alleviated either by a shower or compressed air jet, directed into the nip between the lower slice lip and the breast roll, or a soft rubber wiper lightly pressed on to the wire; these devices also reduce the possibility of streaks caused by water channelling under a wire apron and are especially important when trays are not used. Where forming boards are not possible for reducing the gap between the breast roll and first table roll, a relatively small breast roll can be used and a separate larger roll is then required to act as the turning roll; an advantage of this arrangement is that the smaller breast roll permits a more variable setting of the point of impact of the slice jet without re-quiring the lower slice lip to protrude too far over the roll, thereby increasing the vertical fall of the jet on to the wire (see discussion in **3B.1 2**).

3B.10 2. Other equipment

Reduction of aeration achieved by using trays under the wire to catch table roll backwater has been mentioned several times and there is no doubt that when the return wire is showered with backwater a large volume is carried through to the breast roll and can spoil the underside of the sheet.

Machines having the main backwater pit at the side of the machine always have trays under the wire and it is only when the pit under the wire is used to collect the backwater that the practice of not using trays is sometimes found. Although on some occasions it may be found that leaving out trays does not appear to influence the operation of the machine in any way, if frothing or air-bells on the wire occur replacement of trays is certain to help alleviate the problems caused. Trays are often avoided by the machine crews when they have been badly designed or are too heavy for easy removal and replacement during a wire change. In this case the remedy is obvious, and consideration should be given to using plastic materials for lightness.

Steam showers on the wire, though effective for bursting bubbles when these cannot be avoided in any of the ways mentioned above, are an unmitigated nuisance and make general working conditions and observation of the wire and dandy very difficult. Furthermore, badly designed steam jets drop water on to the sheet and, if too strong, can produce a secondary disturbance in the form of a spray as the bubbles collapse. Mansell and Saunders (6) have suggested using an anti-foam compound spray on to the web with the aid of compressed air. Their experiments in this direction lead them to the conclusion that this was a more effective and cheaper way of removing bubbles on the stock surface but probably the relatively higher capital cost of the equipment compared to a simple steam spray has prevented a more general use.

Stretch in the wire is usually taken up on one, or on longer wires two, rolls with vertical adjustment on a screw; this serves at the same time to set the tension in the wire. Although movement of the stretch roll may be two or three feet, the difference between minimum to maximum lengths of the wire will only be a matter of inches and great accuracy in supplying the exact ordered length is imperative for wire manufacturers. On faster machines the wire tension set by the stretch roll becomes a very important factor affecting wire life and sheet quality so that some indication of the tension is highly desirable both for setting and running the wire more consistently. A load cell incorporated at each end of a suitable roll is on way of obtaining a measure of the wire tension and this can also indicate if there is any difference in tension across the wire. As a final development, automatic tensioning devices enabling the wire to be set (preferably while the machine is in operation) and maintained at any desired tension are becoming more common on faster machines and a number of efficient designs are now available.

For guiding the wire the spade-actuated mechanical movement has proved a most efficient design when properly set up, but with increasing speeds the response for stable correction of a drift in the wire becomes too sluggish and the greater pressure of the paddle on the edge of the wire needed to effect movement of the guide roll more easily causes trouble with cracking. For these reasons air and water jets or photocells are now more frequently used to detect movement of the edge of the wire and initiate appropriate adjustment of the guide roll. Alternatively, the self-acting servo-roll type of guide may be used.

The older type of movable deckle straps were never very satisfactory and if allowed to become too slack or dirty on machines with no trim the resulting rough deckle edge could cause frequent press breaks. The stationary deckle strips now in general use except on slow apron machines can also be troublesome if lumps of fibre collect between the strip and the wire, and their setting is critical on faster machines if edge waves are to be avoided. The stock jet should leave the slice parallel to the wire and the deckle can then be pushed in until it is just contacting the edge of the jet. Some machinemen consider that the vertical line of the strip is best angled outwards as this reduces the tendency for cross-waves at the edges of the jet to bounce off and affect the level further in; on the other hand it is also frequently recommended that the deckle strip is bowed slightly outwards down the wire and unless the strip is vertical it is not possible to do this without leaving a gap somewhere between the strip and the wire. The best setting must in fact be found empirically and the ease with which this proves possible will certainly depend on how smooth the flow from the slice can be made. Flexibility of adjustment with adequate rigidity is most important in the design of the holding brackets but inevitably after some time trouble is likely to occur with the deckles when they have become twisted in all directions in an endeavour to remedy an edge fault; it is then simplest to start from scratch again with a perfectly straight, upright strip. There is also a method of obtaining a deckle using compressed air jets but little information on the advantages of this device has yet become available.

The rubber or leather apron still used on very slow machines with dam-type breast boxes can be a trouble-maker if neglected. It requires careful fixing to avoid leaving any projecting points on to which longer fibres easily collect and should be replaced when cracks or wrinkles appear, or if the end becomes frayed. It is generally advisable not to let the apron become too dry and on some machines an old apron is used for support to reduce wear on the underside from the wire.

Finally, cutters on the wire used for the web edge-trim and feeding-up tail need to be kept in first-class condition. For this reason they always use fresh, filtered water, and require frequent wiping round the edge where splashed fibre collects. A cutter that does not produce a clean straight, vertical jet with no feathering can create an enormous amount of trouble by dragging the trim at the couch and producing a ragged edge that sticks at the presses. To avoid breaking the sheet for cleaning or changing cutter nozzles it may be prudent to have two sets available on the machine.

CHAPTER 3C

RUNNING THE WIRE SECTION

3C.1 DAILY OPERATION

The general problem of operating the wire section efficiently is now considered from the point of view first of day-to-day running and then of general long-term maintenance. Discussion of daily operation will follow the procedure adopted in the other Parts of this book and classify measurements that can be made to assist the machineman into essential, important, and useful categories. In the section dealing with general maintenance and long-term records, frequency of wire changing is given prominence because this is the single most important piece of regular maintenance necessary. Finally, there is a section dealing with the more practical aspects of running the wire section.

3C.1 1 Essential measurements

Measurements which can be classed as essential for running the wire part are those which show the performance of the vacuum systems on the suction boxes and also, when applicable, on a suction couch and pick-up roll. In addition the draw at the couch and, where the drive is from individual electric motors, the power taken by the wire may be included in this category.

With regard to the suction boxes a straightforward vacuum gauge in the main manifold is the simplest indication available. With the type of suction arrangement involving a single manifold carrying water to a separator tank, it is also essential as a minimum to have a sight glass for indicating the level in the tank and a pressure gauge on the extraction pump; these enable performance of the separating system to be easily checked if operation is sluggish or flooding of the boxes is suspected, though it is preferable in addition to have a level controller in the tank operating a throttling valve on the discharge side of the pump.

Apart from showing that the system is functioning as required and that air leaks have not become excessive, the use of the main vacuum gauge depends to some extent on the suction arrangement, and in particular on whether an automatic spring-loaded air relief valve or similar type of regulator is used. In this case the vacuum either varies below a maximum value determined by the regulator setting or, if the relief is continuous, keeps relatively steady. A simple regulator of this type is probably the most common system in use on older machines and the primary function of the gauge may then be regarded as being to set the vacuum in the boxes to the desired level by whatever means of adjustment is available. When there is no vacuum regulator the gauge serves to indicate if release cocks on

275

individual suction boxes at the front side or in some other position need to be opened to prevent the vacuum becoming too high. Also, since the vacuum can then vary somewhat depending on changing air resistance in the sheet, some indication of whether the stock is running wetter or freer on the wire is available, though for this particular purpose to achieve much accuracy a measure of the air flow is preferable as discussed in the next section.

The use of vacuum gauges on suction boxes in a suction couch or pick-up roll is essentially similar to their use in a suction press. They serve to indicate malfunctioning of the system due to inefficiency in the pump itself or to unusually great air leakage at the seals. During a particular making the suction couch vacuum fluctuates due to changes in porosity and consolidation of the sheet, and can be used as an indication of varying making conditions, particularly when similar changes in vacuum occur at the suction boxes. Continuous recording of the vacuum in both suction couch and (where appropriate) suction boxes, with presentation of the two traces side by side, can for this reason provide very useful information on many machines, though some precaution is needed when interpreting relative changes of the two readings because, in comparison with the suction box vacuum, the couch vacuum is in practice affected by changes in solids content of the web (and hence by substance and freeness changes) to only a limited extent. Normally, recording the couch vacuum would not be considered essential, but logging of average vacuum readings over a period is valuable for indicating gradual make-up of the holes in the roll (vacuum increasing as less air is carried round in the holes) and other long-term changes in operation. However, when suction box vacuum is controlled, the suction couch vacuum is the only indication readily available of the stability of making conditions and would then be worth recording if the better alternative of using air flow through the suction boxes is not available.

The draw applied at the couch, whether of the open or felt transfer type, is the most critical of all draws down the machine. The importance of the position of the take-off line and the angle of draw from the wire has been stressed earlier and the effect that the web tension can have on paper quality has already been emphasized. A continuous measurement of draw in this position is a most important guide to the machineman, enabling repeatable conditions to be attained at the couch and, from observation of the apparent tension in the sheet at the draw (i.e. movement of the take-off line), variations in adhesion of the web to the wire can be readily detected. Without a draw measurement, when the web carries further round the couch roll and the draw therefore appears slacker, the machineman cannot know whether this is due to a change in adhesion to the wire or to the draw itself.

A particularly sensitive method of draw measurement has been described by Schröder et al. (95) and can be used for studying the relatively rapid fluctuations (or 'fluttering') of the draw that are observable on many machines. These originate mainly from drive variations caused by changes in power transmission or in load on the drive, and apart from the resultant operational instability they induce, have been shown to affect directly the

substance and strength and stretch properties of the sheet. However, for regular machine use measurement of the draw is simpler at the couch than in other places down the paper machine because it is normally at least 2 per cent. of the machine speed even for pick-up transfer, and can be as high as 8 or 10 per cent. on lightweight papers. Various methods can be used though perhaps for comparative purposes the most suitable continuously monitors the difference between pulse counts from special tachometers mounted on two appropriate rolls.

When practicable a measure of the power consumed by the wire section is invaluable for preventing excessive drag of the wire, and should be associated with a limit warning device to ensure that the machineman notices when consumption exceeds a reasonable level; to give early indication of adverse trends a log should be kept of the ammeter readings. The effect of altering the tension, vacuum on the suction boxes, roll doctor pressure, and other important variables can all be studied by observation of the drive ammeter. Further, provided the normal increase in power consumed over a wire life has been noted for several wires and averaged, a valuable means is available after changing a wire or replacing suction boxes, forming boards, deflectors, etc. to indicate if alignment is poor; in fact often the power demand can be used to assist in obtaining correct setting. Also the drive ammeter often detects cyclic variations more sensitively than is possible by observing fluctuations either of the sheet at a pick-up roll or of the suction box vacuum; these variations may be due to such things as poorly set deckle seals in oscillating suction boxes, excessive slippage of the wire, eccentric breast or couch rolls, or bad cases of uneven stock discharge from the slice.

3C.1 2 Important measurements

Amongst data which are all too rarely available on paper machines but which can provide considerable help in checking and tracing abnormalities of wire operation may be listed an indication of wire tension, air flow from the suction boxes, the vacuum on each individual suction box and, when the system design permits, the flow from each box.

The value of having some indication of wire tension is particularly important for faster machines where it can have a close bearing on wire life and stock disturbances. In such cases the familiar method of setting tension by pressing down with the hand on the wire is too subjective and anyway gives no idea of running tension which is varied by the drag exerted on the wire. Several methods of indicating tension are available and depend on whether or not an automatic tensioning device is used. When automatic tensioning is not used the position of a roll free riding in a vertical slot under the wire provides perhaps the crudest indication of running tension, but a far more accurate method involves measuring the force exerted on an appropriate roll by means of strain gauges. With automatic tensioning devices it is always possible to select the tension precisely at the desired value either hydraulically or by means of weights. Each of these devices will permit repeatable setting of running tension and,

if necessary, systematic alteration during the life of a wire to prevent an excessive increase in the power consumed by the drive.

When vacuum in the suction boxes is largely kept steady by means of a relief valve or some other control system, where practicable a measure of the total air flow from one or all the boxes can be a useful guide to stability of operation. Such a measurement need not be absolute and is obtained very simply by means of a suitable orifice in an individual line or the main air manifold with a differential pressure cell coupled to tappings either side of the orifice; this generally provides a more sensitive measure of the condition of the web in the later stages of drainage than the suction couch vacuum which is sometimes used for this purpose (see previous section). Over relatively long periods the reading obtained in this way is affected by several variables, in particular the condition and setting of the suction box surfaces and deckle seals, and to some extent also the age and cleanliness of the wire; but for shorter periods of a few days or less a measurement of the air flow can prove very useful for several purposes.

Comparison with a continuous substance measurement obtained from a beta ray gauge at the dry-end shows that a large proportion of the variation which occurs in air flow from suction boxes over periods of several minutes is due to fluctuations in the substance. But over longer periods than this any trends which occur can often be accurate indications of alterations in composition of the fresh stuff or retention on the wire. To detect these trends adequately requires a continuous record of the air flow which should preferably be situated by the side of, or on, the same recorder as the substance record, an essential elaboration if full use is to be obtained of this measurement.

Deliberate alterations to the quantity of backwater in circulation, the operating vacuum, or formation conditions also affect this reading and its comparative nature should, therefore, be thoroughly understood by the machineman. But such alterations apart, air flow through the web at the suction boxes will depend on the closeness of the mat and its solids content above the boxes, both of which are functions of drainage and retention conditions and hence primarily of treatment of the fresh stuff. For this reason perhaps the most useful potential which measurement of suction box air flow presents is when it is used in conjunction with a last refiner in the fresh stuff line during intervals between obtaining paper tests or stock tests in the preparation system upon which the overall control of beating and refining will normally be dependent; provided the response to small alterations in the load of such a refiner is reasonably soon apparent on the wire it may be regulated quite effectively to keep the air flow steady. Whether or not this keeps the qualities most desirable in the paper more consistent is, however, a matter for experimental determination.

In operating suction boxes the benefits obtainable from grading the vacuum on individual boxes have been detailed in 3A.31. Considering that these benefits are fairly well-known it is not easy to understand the general lack on paper machines of any indication of the vacuum on each box. The expense of a vacuum gauge on each box is small but alternatively it is not difficult to mount a series of small mercury tubes on the front side of

the machine and connect these to the boxes. In fact the latter arrangement has some merit because the grading of vacuum is more readily apparent, though if the vacuum gauges are also mounted close together almost the same visual effect is achieved and maintenance is less. It has been recommended that vacuum should be gradually increased from the first box approximately up to the box under the dry-line, and thereafter be constant; with vacuum measurement on each box, changing the rate of increase in the earlier boxes and the overall vacuum during normal production can be studied in relation to the influence on average moisture content of the web at the couch and performance of the wire.

As a useful adjunct to measurement of the vacuum in each box, on suitable systems the flow of backwater extracted by each box can be measured. This requires individual drop legs and suction lines on each box, an arrangement which is in any case superior to a single manifold and separator tank but which requires adequate depth below the wire to function; the discharge from each drop leg can be placed into a compartment with overflow at one side across a suitably sized weir into a collecting pit. The level over each weir then serves to give a reasonably accurate indication of the flow from each box, certainly on a comparative basis. With this additional information it should be possible to study directly the effect on dewatering efficiency of varying the vacuum applied in each box, a very valuable facility for any machine especially when drainage capacity limits production.

3C.13 Useful measurements

Several other measurements may usefully be made in the wire part with the object of providing further data on general drainage conditions and of regulating more closely the use of a dandy, upper couch or presser roll, pick-up roll, etc. With regard to the drainage conditions, measurements of consistencies, flows, and so forth in the machine backwater circuit and suction boxes are most important and their observation and control does, of course, contribute considerably to keeping the general drainage conditions steady, but this aspect has already been dealt with in Part 1.

It has frequently been proposed that the flow from one or more table rolls either over the whole width of the machine or a selected width would give an extremely valuable record of conditions on the wire. Certainly when applied to a breast roll discharge such a measurement even on a relatively crude basis could well be valuable for indicating changes in running conditions produced by the many factors which affect drainage when the stock first meets the wire, in particular on faster machines the wire tension and slice geometry. A drainage rate measurement applied on a continuous basis to one or more table rolls, may also prove interesting from the experimental point of view, but the author doubts if such a reading can with the present state of our knowledge provide information which could usefully augment other indications of changes in drainage which are more easy to obtain. Certainly it can be expected that for any particular making at a single speed, changes in the drainage rate will occur due to temperature,

stock conditions and many other factors, but at the present time it is almost certainly more useful to set about keeping these steady by means of other more direct measurements and control applications than to attempt to use an indication of table roll flow as a basis for tracing sources of variability during operation.

A simple measurement of the load of a dandy on the wire and, especially for a driven dandy, any indication of the relative speed with the wire would both be very useful. The load indication can be quite rudimentary, the position of springs at back and front sides or of some relieving weight, and provided the mechanism is kept free from resistance this is better than nothing; for more precise measurement a load cell or statimeter type of instrument could be used, or alternatively with pneumatic relieving the air pressure is sufficient.

Similar remarks apply to the pressure exerted by a presser roll, upper couch roll, or pick-up roll which, if consistently too high, can cause damage to the wire in the form of machine direction cracks. In addition in each case though probably within fairly wide limits, variation of pressure could have a significant effect on the ultimate sheet properties and for this reason also it is a useful facility to have some indication of the load applied, however indirect.

Regarding the relative speeds of dandy and wire, a separate dandy drive and differential speed measurement has several advantages for controlling the running with precision and independent of the pressure of the dandy on the web. By this means an optimum range for the relative speed can be found and kept to without difficulty, and for watermarking to register a ready and closely controllable adjustment is available to take care of changes in shrinkage and other factors.

3C.2 MAINTENANCE OF THE WIRE SECTION

3C.2 1 Wire changing

Changing the wire represents the most frequent and important piece of maintenance, in the broadest sense of the word, necessary to keep the wire section running efficiently. The life of a wire can vary from a few days on very fast machines to many weeks; the reason for removal depends, of course, very much on the machine conditions, though straightforward wear is almost certainly the most common.

As with other clothing used in the paper machine the policy adopted with regard to frequency of changing varies appreciably from mill to mill, but in a majority it is safe to say that the tendency of the papermaker is always to err on the side of obtaining as long a life as possible. If a hole or crack appears the machine is stopped and, unless the damage has become really extensive before it is noticed, a routine repair is effected. This repair may last through to the normal life expected of the wire, but then again it might not and a long series of stoppages for further patching may ensue with the crews anxiously hoping that the wire will last out till the next shut period. Avoidance of such a state of affairs is, of course, the mark of an

experienced papermaker but in making a judgment in any particular case whether to repair or remove a wire it is always helpful if some simple but soundly-based economic criterion is available instead of the normal vague feeling that the wire should be kept on if at all possible.

One approach to this problem is the use of past records to determine an optimum life for a wire which gives, on average, the maximum return. This involves analysis of production and time lost due to repair at different periods through the life of as many wires as possible, and comparison of the cost of a new wire with that of downtime for repairs together with labour costs in carrying out the actual change. The methods and refinements which may be adopted for determining an optimum life in this way are essentially the same as those described for achieving the same object with press felts, to which reference may be made for further details. Such calculations will illustrate the false economy of trying to obtain a few extra days of use from a wire after it has reached a certain age, and it follows that adoption of a standard life based on this will lead to a reduction in the frequency with which risky repairs are necessary.

Nevertheless, accidental damage or poorly regulated running will always necessitate some repairs at one time or another, occasionally quite early on in a wire's life. The machineman or supervisor is then faced with assessing the likelihood that the patch he can put on will last, or whether further trouble may be expected and possibly a reduction in machine speed advisable to carry the wire through to the next scheduled shut period. Such decisions are made easier if two standard costs are obtained: the average cost per hour of the wire, and the average cost per minute of downtime. With the first figure a simple calculation will give the additional cost incurred by changing the wire before the next shut period when it would have been changed anyway; the second figure enables this to be converted to the equivalent of downtime which, when added to the time that would be needed to change the wire, can then be balanced against the time for repair plus the likelihood of further stoppages.

For example, suppose for simplicity that the average cost for the wire is 10s. per hour and the average cost of downtime is 15s. per minute. The machine is stopped to inspect a hole halfway through the week and another 60 hours running will be needed to carry the wire on to the week-end or the next scheduled shut period. Replacing the wire incurs additional wire costs equal to $60 \times 10s. = £30$, or the equivalent of 40 minutes downtime. Add to this the time needed to change the wire which, including preparation time, may be 150 minutes, and the total cost of changing the wire becomes equivalent to 190 minutes downtime. If the hole is small, seeming unlikely to give further trouble and taking perhaps only 10 to 15 minutes to patch and get the machine under way again, it is clear that the wire should be repaired. If on the other hand the hole is already large, experience may indicate that half-an-hour would be needed to complete the job and that even then the patch would need examining and probably replacing at least once a day and possibly once a shift; in this case it is very likely that downtime could exceed 190 minutes and the wire should be changed. The effect of another alternative which may be chosen, running

the machine slower to nurse the wire, can easily be assessed on the same terms by estimating the resulting loss of production and converting to running time at the normal rate.

3C.2 2 Wire records

More than with any other clothing it is essential to keep careful records of the makes and types of different wires used on the machine and their general performance in regard to ease of running. It is customary to include data concerning the life of the wire and this can be very important for the purposes of comparison and for establishing an optimum life. To this end the criterion of performance for each wire may be in terms either of revolutions turned, tonnage made, days or weeks run or some other suitable measure. Of these the first is probably to be recommended (even though to account for varying speeds and downtime it may require a certain amount of calculation if convenient data such as yardage of paper produced is not available); this is because the number of revolutions of the wire is connected closest with wear, the primary cause of deterioration. Cost per unit (per thousand revolutions, ton of paper, or hour) is a convenient means of easy comparison of different types of wire provided it is remembered that any difference in average loss of time for repairing must also be taken into consideration.

It is, in fact, a worthwhile addition to the wire records if the total loss of time required for attention (directly to the wire and not, for example, to removing pitch) is available. The value of this depends on the circumstances but it can be particularly useful not only as a refinement for comparing cost of different wire but also, if the causes of downtime are categorized carefully, as a means of keeping check on the more familiar troubles— accidental damage, edge cracking, holes and so forth. In addition, as a further check on these factors the reason for eventual removal should be recorded if this takes place before the allotted span.

On any particular machine the wire life will be limited by one or more factors. These may be fairly obvious, in which case a course of action to lengthen the life can be defined: better cleaning sprays to overcome making-up, additives to combat corrosion, a change of suction box material or running tension to reduce wear, and so forth. If the factors responsible are not clear from experience then careful wire records may help. More often often, however, a special programme of examining the wires will be necessary. This could involve identifying and finding the cause of faults, and detailed testing of samples of each wire when it is removed from the machine to determine changes that have occurred due to wear, corrosion, make-up and so forth. But collecting such data is more in the nature of a special project in which the results require careful planning and analysis; the tests are not really appropriate as a routine form of checking for the papermaker's purposes and their establishment on this basis may give a false illusion of thoroughness at the expense of a great deal of work.

Even so, certain tests of this type are worth considering as a form of

long-term control and as such may be undertaken periodically on typical used wires with the object of indicating trends and helping to assess the performance of new types of wire. Included in these tests might be: determination of reduction in thickness (related to revolutions turned) to indicate deterioration or improvement in the wear-resistant properties of the wire material, or more likely a change in the abrasion rate at the wire part due to alteration of suction box covers, forming boards, operating vacuum, etc.; micro-photographs of the knuckle surfaces as an indication of roughness caused by grit and other hard particles; assessment of the change in drainage properties of water through the wire (difficult to accomplish with any accuracy and requiring a specially-designed apparatus) to assess changes in the degree of making-up or overall corrosion; and measurement of the tensile and stretch properties of the wire to determine reduction in strength in relation to that of thickness. Such data when available for typical wires also assist in detecting the reason for a wire failing earlier than expected. For example, excessive abrasion of the knuckles might indicate a deficiency in the cleaning system or unusually dirty pulp; a drop in tensile strength even though the thickness reduction is less than usual could point to a wire manufactured from poor metal.

3C.2 3 Other maintenance

Many items in the wire section need frequent attention and the responsibility for this and the way in which the maintenance is organized depends essentially on the attitude and progressiveness of each mill. At one end of the scale little or nothing is renewed until the evidence of neglect becomes apparent in the quality of the paper or in general smoothness of running the wire part. At the other end of the scale each item of equipment is either renewed at regular intervals or examined and renewed when a specified deterioration has taken place. The wire part is the area of the paper machine most sensitive to neglect in this respect but it is not appropriate here to discuss the techniques and economics of long-term maintenance organization, and attention is confined to detailing the main items of equipment requiring regular inspection.

On machines using couch jackets and pick-up felts these, of course, need regular renewal. The requirements for adequate records in dealing with this are essentially similar to those for press felts, and as these are considered in detail in Part 4, further discussion is unnecessary. The same applies to the maintenance of suction box seals, internal sprays, hole condition, etc., of a suction couch, which is basically similar to the suction press. Also the camber on an upper couch roll, squeeze roll, rubber presser roll, or on any roll inside the wire, though normally very small, nevertheless should be checked at fairly frequent intervals and the results, possibly expressed in the form of wear curves, may then be treated in the same manner as described for press rolls. Neglect of these items can eventually affect running of the wire as it becomes increasingly difficult to guide and frequent ridging is likely; also evenness of cross-web solids content at the couch deteriorates, culminating in an increased frequency of breaks at

that point and a worsening of the evenness across the sheet at the reel-up.

The condition of all doctors in the wire section is especially important and the blades on each doctor need regular attention; the angle of the blade to the roll should also be checked at intervals as particularly on smaller diameter rolls relatively little blade wear has an appreciable effect on the angle. Beside the doctors, other items of equipment such as deckle straps or strips, wire aprons, the guide and stretch mechanism, sprays, forming board and deflector surfaces, cutter nozzles, guard boards, etc. should all preferably be placed on a preventive maintenance schedule and a proper record kept of the types in use, their life, condition when removed and so forth. Cracks or perishing of deckles and aprons, and nicks in the surface of a forming board may appear insignificant but can cause a surprising amount of trouble.

The breast roll needs to be checked periodically for alignment, especially when shake is used. Observation of the wire during running will indicate any unevenness in rotation of either breast roll or table rolls and this should never be allowed to continue for long as tendencies to eccentricity or flats on a roll rapidly become accentuated. Grooved rolls need more careful cleaning than solid rolls to prevent an accumulation of fibre, scale, and other debris which are liable to break away unevenly causing the roll to extract more water at one part than another. Dandy rolls require thorough off-machine cleaning and examination each shut-down and records of performance for each dandy should be similar to those described for wires.

Suction box covers should always be attended to before the surface has worn into hollows and loss of vacuum or difficulties guiding the wire occur. Dressing of covers off the machine should always be done with the suction box supported exactly as in the wire frame to allow for the sag in the middle; if water in the box under normal running conditions makes a significant contribution to the sag, the box should also be part-filled with water before dressing in this way. It is useful to plane down each box in rotation over a suitable period, though whether in fact this is possible depends on the relative rate of wear of the wire and boxes; on faster machines it may be necessary to attend to almost every box at each wire change, though when this state of affairs exists on slow machines it may well be that bad alignment of the wire is creating unequal wear.

It is an advantage to start up with no more than one or two freshly dressed boxes at the same time to avoid a condition which may produce too much drag on the wire and make it difficult to obtain the normal suction. On replacement, careful alignment of the box top to be just parallel and in even contact with the wire surface, and at right angles to the run of the wire, is essential to prevent guiding trouble or excessive drag. For fixed deckle machines, setting the position of the box deckles is also important, especially when the boxes are oscillated, to ensure that the suction area does not extend outside the deckle edge of the sheet. A record of the time spent dressing boxes from each position under the wire, together with the frequency with which covers have to be replaced, provides important data

as conditions of speed, suction-box vacuum, type of wire, and so forth change over the years. It also, of course, provides essential information with which to compare the performance of new cover materials.

3C.2 4 Long-term records

For the purpose of long-term records tests at the wire section are preferably obtained after the wire has bedded down, i.e. when the power consumed by the drive has approached the normal maximum. This will enable comparisons to be made without requiring allowance for any effect that the age of the wire may have in requiring operation at a different tension or suction box vacuum.

Special measurements which should be taken in a wire section test will include firstly any of those considered earlier for which instruments do not already provide an indication. These are: vacuum on each suction box and the extraction rate, total air flow from the boxes, wire tension, and whenever possible the load applied by an upper couch or presser roll. Vacuum on each box is easily obtained from a tapping specially made for the purpose in the ends of each box. In order to measure the extraction rate when the water is not all discharged down a drop-leg, probably the simplest method is that involving addition of salt solution at a fixed rate through a tapping at the front-side of the box and determination of the equilibrium salt concentration in samples drawn off from the extraction pipe before it meets the main manifold. Measurement of air flow through the boxes can be done with a pitot tube and some idea of the wire tension can be obtained for comparative purposes when the wire is stationary by noting the depression caused by lowering a roll of known weight in the middle of a convenient run of the wire (see reference 49).

The flow from a number of table rolls and the breast roll could prove useful for long-term records though this is hardly practicable unless troughs are specially designed to catch the water and channel it to a convenient measuring pipe at the side of the machine. Such equipment may not be convenient to leave permanently in position under the wire. Alternatively, in the drier section of the wire it is possible to measure the solids content of the web (this is best expressed in terms of water-to-fibre ratio); this may be achieved by using a slit-shaped air nozzle to blow off lumps of stock from underneath the wire into a receiving pan. Though the accuracy and repeatability of the results obtained by this technique leave something to be desired, they can be sufficiently reliable to provide useful data. In this way determinations of solids content along the table roll section, immediately before the suction boxes, in between the boxes and before the couch can be made. With practice this does not require too much loss of production and is conveniently organized in association with press and drying section tests for which the sheet also needs to be broken down.

This data permits the dewatering efficiency of the couch to be calculated and provides a means of cross-checking the extraction rates of the suction boxes when these are measured separately; too close agreement is not to be expected especially for faster machines and those making lightweight paper

because splashing and breaking up of the web on the wire make it difficult to obtain a representative sample. The position of the dry-line and power consumed by the wire section should also be noted.

3C.3 PRACTICAL POINTS

From the practical point of view, operating the wire part of a paper machine requires more training and experience than any other job in a paper mill. It also requires a detailed knowledge of the individual characteristics of the machine. What follows, therefore, can only be of limited value although it is hoped that it contains some information and points of use to the person with little or no experience of actually running a wire part.

3C.3 1 Start-up

The factors in starting-up the wire part which have the most direct influence on how quickly saleable paper is produced are those affecting formation, in so far as it is governed by the flow on to the wire, and substance; these particular aspects have already been dealt with when describing the wet-end flow system. With the exception of machines where a dandy or top couch roll is used, the wire part itself probably affects the start-up directly only when something is overlooked which prevents the normal procedure taking place smoothly. In other words the machineman needs to be concerned primarily in checking that all the devices comprising the wire part are functioning satisfactorily before and after the sheet comes on the wire, as opposed to actually setting the conditions to those desired (as with the stock flow system) or ensuring that conditions are as near as possible to those eventually pertaining when the sheet is up (as with the press and drying sections). This emphasis requires painstaking attention to detail particularly with regard to starting the wire itself, a task in which damage is easily caused as a result of a small oversight. To assist the machineman to do a thorough job it is very useful to provide a comprehensive check-list that he can refer to.

Before the wire is first set in motion it should be thoroughly inspected and jetted inside and out to ensure so far as is practicable that no objects have become lodged where they can cause damage in the nips between the wire and rolls. The wire is then very slowly crawled round, a foot or two at a time, while the jetting is continued and any doubtful areas are cleaned with a grease solvent, with the aid perhaps of a wire brush or steam jet. When the wire is considered to be thoroughly clean it may be stopped for a while until the stuff is ready, though it is preferable when water is being pumped round the system and through the slice that the wire is kept running slowly round. This applies particularly when the water is being heated in the backwater pit as the wire will then become gradually warmed with the rest of the system, an added assurance that rapid temperature changes when the stock comes on the wire do not cause the sudden appearance of ridges.

When the wire is ready to be put in motion after cleaning, the action of

the sprays should be checked to ensure that the pressure is adequate and the coverage even. The normal tension is then set and the operation of the guide mechanism carefully checked with somebody posted ready to make an immediate switch over to manual operation or work the hand guide if the wire looks like going over the edge of the table rolls. All undriven rolls should be glanced at to ensure that they are in motion and the scraping action of the doctors should appear smooth and continuous. This is the time also for a first inspection of other items of the equipment which are easily overlooked: the smoothness of shake operation, the jets from cutter nozzles, the deckle straps or strips, the wire apron, breast roll wire wiper, tray positions, etc.

Finally the vacuum pumps on the suction boxes and, when applicable, on the suction couch and pick-up rolls are started. The presser roll or jacketed couch roll normally have no separate drive and are lowered on to the wire; where a new jacket needs to be well run in the roll may be lowered while the wire is being jetted. Pressure on the wire should be light until the sheet passes through to avoid damage to the wire and lessen the possibility of the sheet being picked up as it first passes underneath (an occurrence which is, of course, particularly troublesome with a jacketed couch roll as it might ruin both wire and jacket).

Water from the machine pit should be circulated first while head at the slice and other flow box conditions are set, then when the stuff is turned on the substance of the sheet will be low at first and gradually creep up to the desired value as the backwater consistency approaches equilibrium. There is little risk with this procedure that the vacuum at the suction boxes becomes excessive due to high air resistance of the mat and causes the wire to freeze, a most undesirable accident. But as a double insurance the vacuum regulator may initially be set at a lower value than normal and then re-adjusted shortly after flow on the wire has been established.

With the sheet on the wire the vacuum in individual suction boxes requires setting and where a separator tank is used a check is immediately made that this is functioning correctly. The suction box deckles should also be examined to ensure that the edges of the sheet are not too wet (leading to trim troubles and crushing at the couch) and that air is not being sucked in (this may give an audible indication but otherwise reliance must be placed on the suction box vacuum gauge or air-flow indication). If one or more boxes are freshly dressed an especially careful examination is required to make certain that they have been replaced level and are not rubbing hard on the wire and creating an excessive load on the wire drive, or causing the suction to gulp or oscillate. To give the sheet time to approach final running substance it is then appropriate to check again the action of the shake, cutters, sprays, dandy wiper, etc. and note any disturbances to the flow at the edges, adjusting if necessary the deckle straps and positioning the cutters to give the required trim width.

On older machines without a hog-pit it will be generally considered preferable to pass the sheet over to the presses as soon as possible. But before this is done it is far better, when applicable, that the dandy is lowered. On faster machines to get up speed fast enough the dandy is

occasionally lowered before the stock passes on to the wire; this is an unsatisfactory practice unnecessarily endangering the dandy, and it is much more sensible to provide the dandy with a helper drive. The dandy should have been thoroughly sprayed before lowering, as should the presser roll when used.

For a jacket couch, preparation should have been made with as much care as for a press felt. The ends require inspection and tightening if necessary, and a thorough checkover is made for grease marks. Care must be taken to wet out the jacket evenly, possibly with a hot water high-pressure hose, but even then occasionally trouble may occur as the sheet tends to follow up the jacket; this is more likely to happen when the sheet is too wet or the jacket dirty, but a mixture of resin size and china clay poured into the guard board or squeeze roll nip is generally thought to help avoid picking. Weights on the jacket couch or presser roll should immediately be adjusted to normal, and if sprays are used on the squeeze roll these are also checked.

If this procedure is carried through efficiently, by the time the substance of the sheet is approaching its ultimate equilibrium value other properties of the web at the couch should also be comparable to normal. In particular the solids content and wet-strength derived from adequate consolidation at the dandy and couch should be sufficiently close to their eventual values to make the action of transfer to the presses little different from any other occasion.

For feeding across to the presses the main cutter is positioned to give a tail four to six inches in width. With open draws the tail may be picked by hand from the wire (aided by a lump of broke), or more commonly on faster machines it is blown over by means of a special air jet in the suction couch. To assist passing over the tail a light aluminium lead roll may be initially raised by hydraulic pressure at the front side, and then immediately lowered; such a roll near the wire is very useful for restricting movement of the web take-off line but needs to be kept clear of fibre clots or the sheet is marked. With a suction pick-up roll either the roll itself is lowered or a forward drive roll moves the wire up into contact with the roll; transfer may be assisted by diverting extra suction capacity to the pick-up box but normally little difficulty occurs with this method of couching and it is common to feed up the whole sheet through the first press at once without first passing a tail.

Whenever practicable it is preferable from the point of view of the press that the tail is widened straightaway after being successfully fed through. For this an automatic widening device carrying the cutter across operates more smoothly and safely than movement of a connecting hose by hand, and permits the system to be tied in with one or more break detectors, normally of the photoelectric or ultrasonic type. When installed at intervals down the machine these detectors can actuate the cutter to narrow the sheet to feeding-up width and reduce broke gathering in the drying cylinders. Also on some machines it may be possible to detect tears starting at the edge of the web at the couch or presses with sufficient speed to enable a cutter positioned centrally above the wire to be turned on; this stops the

tear spreading across the full width of the sheet and causing a break, so the cutter may then be made to traverse automatically to the edge to restore the sheet, returning to the centre after the water has been turned off. Difficulty can be experienced at first as the tail end tends to follow round the wire; a tighter draw may help to overcome this if the sheet is reasonably strong but it should be possible to return close to the normal operating draw as soon as the cutter is taken across.

Once the sheet is through the presses the machineman may return his attention to the various parts of the wire. Sprays are turned over to white-water if this does not function automatically by means of a head tank feed or a non-return valve when the pressure is high enough; a check is made that the trim is passing smoothly to the hog-pit without tending to tear at the point of separation or follow the main sheet, and the couch or pick-up deckle positions adjusted if necessary; the dandy is examined for picking, the jacket operation is checked; the appearance of air-bells on the stock surface is noted, and so forth. These points will be given a little more attention when describing what to look for when the machine is running.

There is one adjustment which the machineman is likely to make as soon as possible, that of setting the dry-line across the machine. The use of the dry-line for giving an early indication of the evenness of substance distribution across the web has been mentioned previously but it is appropriate here to stress that ideally the line should only be taken as an indication which is useful at this stage of the start-up before proper substance tests can be taken on paper at the reel-up. The reason for this is that the dry-line profile is influenced not only by the substance at any particular point across the sheet but also by any factor which affects the drainage rate unevenly: a partly clogged grooved-roll, dandy, or suction box; uneven dandy pressure; sagging deflectors or forming boards giving unequal action; a breast roll slightly offset extracting more water one side than the other; the wire partially made-up due to uneven spray or couch action. All these and probably many other small differences could produce a bulge in the dry-line even with a perfect substance profile. The dry-line position is highly important as an indication to the machineman that the overall conditions with regard to drainage rate and solids content at the couch are satisfactory, and also relative movement of the line and the frequency of tongues spurting out give some indication of the stability of the stock and backwater system; but variations across the machine, except gross ones which occur, for example, when the deckles are badly set, need more careful interpretation.

3C.3 2 Shut-down

The procedure for stopping the wire section either for a scheduled shut or for an emergency inspection involves relatively little trouble. Once circulation of stock through the slice ceases with stoppage of the pumps or opening of a dump valve, the wire can be brought to a standstill. Until the wire is stopped it is advisable to leave the suction box vacuum pump on or the wire may start wandering about. Sprays are either turned off or, if the wire is subsequently cleaned by crawling or inching round with the sprays on, then when the action is not automatic a change must be made

immediately from whitewater to fresh water to prevent damaging the wire or getting it clogged with fibre while almost stationary.

For a scheduled shut-down, the upper couch roll or presser roll should be raised and, particularly in the case of the former, given a thorough clean. This applies not only to the jacket but also, when applicable, to the guard board and squeeze roll both of which should be raised off the jacket. A dandy needs to be removed immediately from the machine and cleaned because if fibre is allowed to dry in the delicate mesh permanent damage may be caused when trying to remove it.

Particularly when stock has been running at a high temperature and a cold fresh-water shower is turned on, the wire should be slackened back to permit easy shrinkage as cooling takes place. A strong jet of water, preferably warm, is generally sufficient to remove debris from the wire, but if slime or pitch is present additional treatment as described in 3C.3 5 is necessary. Rolls also require jetting, particularly when grooved, and the pressure of all doctors should be relieved. Finally items like the deckles, apron, forming board surface, doctors, showers, cutter nozzles, and so forth should be given a routine inspection, and arrangements made when necessary for renewal. The wire itself is also checked over for holes and cracks. With hardwood suction box covers and wooden doctors water may be left playing on the surfaces during a longer shut period to prevent them drying out and cracking.

3C.3 3 Changing and running the wire

When changing the wire the first step is to remove the old one; this is usually done by cutting across the wire at the couch and bundling together the folds as the roll is slowly crawled round. With the old wire off, before hosing down the opportunity should be taken to inspect various parts of the wire section which are normally difficult to see: the middle parts of table rolls, doctor blades, apron, grooved rolls, etc. For fixed deckle machines the suction-box edge seals may also be checked and re-set, particularly if trouble with the edges of the sheet has necessitated a temporary adjustment at some time which may not have been corrected satisfactorily.

In addition, the positions of the table rolls, forming boards, deflectors, and suction boxes may be checked for alignment, particularly if any rolls have been changed or surfaces planed. This can be carried out in several ways but perhaps the most satisfactory is to stretch a thin steel wire at both sides of the machine at a gap of $\frac{1}{8}$ in. or so above the normal run of the machine wire, then check or set each clearance to this. Though ensuring correct vertical alignment this check would not detect if one end of a roll or suction box were displaced horizontally compared to the other; this can be done only by comparing diagonal measurements to the opposite ends of a roll known to be square to the wire (preferably the breast or couch roll) but this task should not be necessary very often.

The routine for actually putting on a new wire depends, of course, on the basic method designed for the machine and it is of no value here to discuss this in detail. So much depends on the experience and training of the

changing crew and whether or not a soundly thought out procedure is followed. In this respect there is probably much merit, particularly for mid-week changes where saving of time is highly important, in having a single crew specifically trained for this task and having the whole job method studied with particular reference to the danger-areas where greater precaution is needed. Wires are easily damaged and the attention given by a good crew to such little things as unpacking and lifting carefully from the crate and removing all obstacles, hoses, tools, etc. from the machine-room floor before starting the operation can save much expense. All changing equipment, particularly the surfaces of the poles, should be kept scrupulously clean and adequately protected from warping when not in use.

With the wire on, the procedure for checking over follows that detailed in the section on starting-up. A new wire will often require more careful inspection and cleaning with a grease solvent due to the handling, and the seam or any odd kinks which have appeared may need smoothing down by pressing (or in the case of plastic wires lightly ironing at a set tempera-ture) with a flat board underneath which is preferably kept specially for the purpose. Greater attention is also necessary to check the alignment of the wire and watch for signs of a ridge appearing; when first crawling round a few turns should be made with the wire fairly slack before it is gradually tightened up to near eventual running tension.

During running, provided the guiding mechanism functions satisfactorily the wire itself should not require much attention except an occasional touch to the hand guide to bring the automatic guide roll to a more central working position. In the absence of an automatic tensioning device the stretch roll will be adjusted at intervals to take care of changes in the length of the wire as it expands under tension and for this purpose an indication of running tension is particularly useful. Observation is always necessary to detect the early appearance of any faults or of deposits of pitch and slime which affect the drainage in patches, and this the machine-man does continually in his constant watch on how the sheet forms on the wire.

3C.3 4 Changing and running a jacket

Although jacket couches are now obsolete there are still a large number of slower speed machines which use this arrangement. Perhaps more than any other piece of clothing, selection and running of a jacket is individual to one machine and in adverse conditions a poor jacket can create an enormous amount of trouble.

When changing a jacket the old one is cut off lengthwise and gathered up as the wire is inched round. After jetting out the roll with hot water the new jacket is opened out and edged over the roll, care being taken to ensure that the nap runs in the correct direction. This operation should normally not take long though a great deal of struggling is necessary if the jacket is slightly undersize and needs to be stretched; for this reason the inside length of the jacket should correspond to within a fraction of an

inch to the ordered size. After sewing or tying up the ends, shrinking of the jacket must be done with special care and it is preferable to use a spray which can apply hot water evenly across the surface. As the jacket becomes thoroughly wet the guard board or squeeze roll is put down to help condition the felt and flatten the nap.

A final examination of the surface of the jacket is advisable to ensure that there are no hard lumps caused by the roll or a sliver of wood under the jacket; this would rapidly lead to a ridge in the wire. The tightness should also be sufficient to prevent the jacket wandering or ruckling up with the squeeze roll or guard board at normal pressure, and to ensure this the ends may need to be undone and pulled tighter.

Controlling a jacket during running is straightforward so long as it has been adequately shrunk and tightened. The seam normally has a slight lead in the middle from the small amount of camber on the roll, but if this gets excessive greater load on the ends of the couch roll is required. If the seam leads at one side it is likely that the guard board or squeeze roll pressure is unequal at the ends and a little extra load on the leading side is required. Likewise a tendency to run over to one side may be overcome by slightly relieving the load on that side. Alterations to the load on the board or squeeze roll in this way should not be allowed to become excessive or the pressure of the couch roll on the sheet will become uneven, causing the jacket to receive unequal wear which will ultimately accentuate the difficulty of running. For the same reason every effort should be made to avoid applying unequal weight to the ends of the couch roll to correct a fault either of drainage earlier up the wire or of the jacket itself.

Jackets become dirty very quickly and frequently need to be given a thorough clean by jetting with hot water. The nap can also be brushed up with felt teezers though the long-term benefit of this in an older jacket which is well clogged and worn is doubtful.

3C.3 5 Checking the wire section during running

The machineman spends most of his time watching the wire section and a list of the points he looks for, or should look for, would fill many pages; even then it would be impracticable to attempt to detail them all for so much is essentially individual to each machine. All instrument and recorder readings should be regularly checked and attempts made to explain movements which occur beyond the normal expected limits of variation; when required a log is completed. The working of all the ancillary pieces of equipment should also be systematically inspected—a simple check list can be very useful for this purpose.

At the same time the most important criterion of successful operation, the sheet quality, is carefully checked each time a sample is available; apart from the general appearance of the sheet, any blemishes or faults which are present are noted and explanations for them sought. These may be identified as coming from fairly obvious sources such as air bells, or they may originate in many more obscure ways due to such things as water passing unevenly over a deflector surface. So far as possible, sources of

trouble have been mentioned earlier when dealing specifically with faults originating at each item of equipment, but connecting a particular fault with its cause is all too frequently extremely difficult and it is in this realm that the experience of a good machineman is invaluable.

The machineman takes continual note of the appearance of the sheet on the wire and the general forming conditions, with particular emphasis on any sign of unevenness which recurs as the wire comes round each revolution. In this way a small crack or hole in the wire can be detected very quickly and rectified before becoming serious. The accumulation of slime or pitch in patches on the wire can also be noted by observing unevenness of drainage, though often the first indications of this sort of trouble, particularly on faster machines, occur when holes are noticed in the paper and breaks occur.

Early detection of slime and pitch on the wire may prevent the necessity for a thorough clean-up of all parts of the wire involving removal of forming boards, doctors, and suction boxes. Both deposits can be difficult to dislodge and the decision to shut a machine for cleaning is not made easier by knowing that once started there is a tendency for both slime and pitch to accumulate more rapidly, particularly on those areas already affected which may not get completely cleaned. Sometimes, especially in the case of pitch trouble, time can be saved whenever practicable by removing suction boxes one at a time before stopping the wire; this has the advantage of preventing any pitch on the boxes from being pushed into the wire mesh when the machine is shut. Removal of slime from the wire mesh is generally easiest with a steam jet, but to dislodge bad patches may need a suitable solvent together with scrubbing with a brush with hard bristles (but not so hard as to scratch and wear the wire). Pitch is tackled in a similar way and often chalk or clay may be rubbed over the affected areas first to help push it out of the mesh. In both cases it is useful to place a special tray under the wire to collect the particles blown through, otherwise when re-starting the backwater system may be full of small specks which give further trouble.

Some useful indications can also be obtained from watching the surface of the stock mat for other types of irregularities. The line on the surface made as the mat passes over each table roll should be perfectly straight and stable; wavering indicates variations in the mat conditions and a regular oscillation may be traced to unevenness in the roll itself, indicating the desirability for changing and re-covering, or to a vibrational disturbance in the stock flow system. The couch line or take-off should also be even without fluttering, and a permanent depression in the line could indicate a blocked spray causing the wire to become made-up or some other fault affecting drainage rate at that particular position across the mchine.

Changes in position of the take-off line which occur under unaltered conditions of the draw tension can also give a pointer to changes in the general substance level and the stock drainage conditions: if the take-off line moves back up the wire (i.e. the draw appears tighter) and at the same time the dry-line has moved forward on the wire, it is likely that the sheet has become heavier; but if on the other hand the take-off line moves back

but the dry-line has also moved back, then on many machines this is a clear sign that the stock is freer. Opposite indications are given when the take-off line moves further forward on the wire (i.e. the draw appears slacker): in this case if the dry-line has also moved forward on the wire it is quite likely that the stock has come wetter; on the other hand, if the dry-line has moved back the sheet is probably lighter. To make this clear, changes in the position of take-off line and couch line are produced as follows:

Dry-line movement	Take-off line movement	Change in property
Forward	Back (appears tighter)	Sheet heavy
Back	Forward (appears slacker)	Sheet light
Forward	Forward (appears slacker)	Stock wet
Back	Back (appears tighter)	Stock free

The validity of these interpretations depends, for any particular machine, on the relative movement of the dry-line that occurs as a result of fluctuations in sheet substance or stock wetness; on some machines the degree of alteration in either substance or stock wetness which is normally encountered during operation may affect the drainage rate, and hence the dry-line position, much more than the other, and so becomes the dominant factor determining the position of the dry-line. Further, the validity depends on the extent to which changes in adhesion of web to wire at the couch, and also (since it alters the effective tension) in the stretch of the sheet in the open draw, are produced on the one hand by alterations in the solids content at the couch, and on the other by changes in composition of the sheet as a result of differences in stuff treatment. Normally, for example, a drop in solids content occasioned by a substance increase will reduce adhesion to some extent (causing the take-off line to move back up the wire); but if the stock works wetter on the wire, though this results in a similar forward movement of the dry-line, the take-off line tends to move in the opposite direction (forward down the wire) due to a combination of greater adhesion to the wire and greater stretch occasioned by the change in stock composition (the latter because greater stretch lessens effective tension for a given draw). Despite these qualifications, the relationships listed above certainly appear to occur to a significant extent on many machines and the machineman finds that careful observation of such signs, together with similar indications that may be obtained at press draws or from the vacuum on the suction boxes or a suction couch, enables him to detect changes and make corrections far sooner than if he waits for confirmation from test results on the paper.

Breaks at the couch are often the first sign of trouble and require some ingenuity to remedy because of the numerous sources that are possible. Any weakness in the sheet caused by uneven drainage at some point of the wire due to pitch, slime, or other causes may produce a break which is more likely to occur at the couch than anywhere else; in addition lumps of fibre breaking away after accumulating in the breast box, slice lip, wire apron or other places, and poor edges caused by the deckle, dandy or

unevenness of contact at the couch, these and a host of other minor ailments can all first show themselves at the couch.

Trouble can also result indirectly from quite a small alteration made by the machineman in the course of his inspection of the wire part; for instance, slackening back the tension in the wire as it ages might increase the wrap round the breast or table rolls to just the extent which causes an appreciable increase in drag on the forming board or deflectors, and this in turn affects the stability of draw at the couch making the presence of occasional faults in the sheet which hitherto passed the couch successfully suddenly sufficient to create a break. Much of papermaking is affected by the occasional appearance for no known reason of trouble of this nature which suddenly exhibits its presence by causing breaks at the couch or press, or by making blemishes in the paper, and then as suddenly disappears followed by a sigh of relief from the operators. More instrumentation and control, better maintenance procedures, and the keeping of comprehensive long-term records should reduce such occurrences considerably, but it would be an optimist who predicted their eventual elimination.

REFERENCES

(1) Hansen, E.: 'The Distribution of Filler in Paper.' TAPPI 34, 4, 180. April, 1951.

(2) Dixon, W. B.: 'The Operation of a Stacked Press With Vacuum Transfer on an English Newsprint Machine.' P. and P. Mag. Can. 53, 11, 115. October, 1952.

(3) Hendry, I. F., Mardon, J., Scruton, H., and Wilkinson, D. M.: 'Drainage on a Tissue Machine Wire Table.' Proc. Tech. Sec. 33, 3, 603. December, 1952.

(4) Rance, H. F.: 'The Influence of Papermaking Variables upon Sheet Characteristics.' Proc. Tech. Sec. 33, 1, 173. February, 1952.

(5) Brauns, O. and Oskarsson, R.: 'Drainage at the Flat Boxes and Suction Couch Roll.' Svensk Pap. 56, 18, 691. September 30, 1953. (In Swedish). Also in English in Paper Maker 127, 3, 190. March, 1954.

(6) Mansell, G. F. J., and Saunders, K. C.: 'A Novel System of eliminating Bubbles on the Fourdrinier Wire.' Proc. Tech. Sec. 36, 3, 535. October, 1953.

(7) Paton, A. W.: 'Machine Wire Maintenance.' Proc. Tech. Sec. 34, 3, 437. December, 1953.

(8) Andersson, O., and Bergström, J.: 'Influence of Differential Speeds Between Stock and Wire on Sheet Properties.' TAPPI 37, 11, 542. November, 1954.

(9) Bennett, W. E.: 'Quantitative Studies of Water Removal by Table Rolls.' TAPPI 37, 11, 534. November, 1954. Also P. and P. Mag. Can. 55, 13, 131. December, 1954.

(10) Brauns, O., Bergström, J., and Svenson, A.: 'Formation of the Web on a Paper Machine Wire. The Influence of Shake.' Svensk Pap. 57, 19, 693. 1954. (In Swedish).

(11) Finger, E. R., and Majewski, Z. J.: 'Sheet Formation on the Fourdrinier Machine.' TAPPI 37, 5, 216. May, 1954.

(12) Holden, H.: 'Some Observations on Suction Couch Rolls, Suction Press Rolls and Vacuum Transfer.' Tech. Bull. Tech. Sec. Brit. Paper & Board Makers' Assoc. 31, No. 1 : 7–12. February; No. 2 : 41–6. April, 1954.

(13) Lyne, L. M., and Gallay, W.: 'Studies in the Fundamentals of Wet-Web Strength.' P. and P. Mag. Can. 55, 11, 128. October, 1954.

(14) Nordman, L.: 'Laboratory Investigation of Water Removal by a Dynamic Suction Box.' TAPPI 37, 11, 553. November, 1954.

(15) Underhay, G. F.: 'Drainage Effects and Two Sidedness.' TAPPI 37, 11, 547. November, 1954.

(16) Alston, M. P., Goodhew, I. E., and Chapman, J.: 'The Study of Formation on the Fourdrinier Wire.' Proc. Tech. Sec. 36, 3, 535. December, 1955.

(17) Baggallay, M. B.: 'Some Theories and Experiments in Couching.' P. and P. Mag. Can. 56, 9, 131. August, 1955; also Canadian Tech. Sec. Proc. p. 517, 1956.

(18) Duskin, A. W., and McCaughan, A. C.: 'What Crosset learned about Grooved Table Rolls on a Light Weight Machine.' Paper Trade Journal 139, 51, 48. December 15, 1955.

(19) Hendry, I. F.: 'Suction Couch Rolls—Some Observations on their Performance and Effect on the Paper.' TAPPI 38, 9, 163. September, 1955.

(20) Brecht, W.: 'The Effects of Wire Shake.' Woch. fur Pap. 84, 11/12, 446. 1956. (In German).

(21) Burkhard, G., and Wrist, P. E.: 'Investigation of High Speed Paper Machine Drainage Phenomena.' P. and P. Mag. Can. 57, 4, 100. March, 1956.

(22) Mardon, J. and Shoumatoff, N.: 'Flocculation, Formation and Headbox Design.' Part IV. P. and P. Mag. Can. 57, 3, 305. Convention Issue, 1956.

(23) Robinson, W. F. E.: 'The Instrumentation of a Paper Machine and the Results Obtained.' Proc. Tech. Sec. 37, 2, 217. June, 1956.

(24) Boiteux, P.: 'The Effect of Drainage Characteristics of the Machine Wire and of the Machine Speed on the Wear of Suction-box Covers.' Assoc. Tech. Ind. Papetiere, Bull. No. 5 : 192–8. 1957. (In French).

(25) Burnett, R. W.: 'Vacuum Transfer from Wire to Press Section.' P. and P. Mag. Can. **54**, 11, 132. November, 1957.

(26) Hitchings, R. G.: 'The Effects of Shake in Slow Speed Fourdrinier Operation.' Paper Trade Journal **141**, 40, 42. October 7, 1957.

(27) Jordansson, L.: 'The Press Section with Vacuum Transfer. Part I. General Operating Conditions and Water Removal.' Svensk Pap. **60**, 5, 59. 1957. (In Swedish).

(28) Müller-Rid, W., and Pausch, G.: 'Difficulties in Sheet Formation on the Wire of a High Speed Paper-machine.' Zellstof und Pap. **6**, 10, 307. 1957. (In German).

(29) Pritchard, E. J.: 'Two Techniques for Studying the Distribution of Loading in Paper.' Proc. Tech. Sec. **38**, 2, 425. June, 1957.

(30) Telepnev, A. N., and Sokolov, N. N.: 'Sheet Drainage at the Suction Boxes.' Bumazh. Prom. **3**, 5. 1957. (In Russian).

(31) Cole, E. J.: 'How the Sheet is Laid on the Wire.' Paper Trade Journal **142**, 49, 44. December 8, 1958.

(32) Dixon, P. H.: 'A Comparison of the Operation of Two Wet Felts.' Also Discussion. Proc. Tech. Sec. **39**, 2, 173. June, 1958.

(33) Friedlander, P. H.: 'The Measurement of Fibre Orientation in Newsprint with respect to the Machine Direction by X-Ray Diffraction.' P. and P. Mag. Can. **59**, 1, 102. January, 1958.

(34) Gavelin, G.: 'The Case of the Open Draw.' Svensk. Pap. **61**, 9, 282. May 15, 1958.

(35) Judt, M.: 'Fibre Orientation in Paper.' Das Papier **12**, 21/22, 568. 1958. (In German), Summary in Tech. Bull. Tech. Sec. Brit. Paper & Board Makers' Assoc. **36**, 4/5, 128. August/October, 1959.

(36) Kitano, A.: 'Post-up transfer from Wire to Press Section.' Paper Trade Journal **142**, 14, 27. April 7, 1958.

(37) Mardon, J., Truman, A. B., O'Blenes, G., and Meadley, K.: 'A Consideration of the Factors Involved at the Open Draws at Couch and Presses of Fourdrinier Machines.' P. and P. Mag. Can. **59**, 9, 135. September, 1958.

(38) Moen, C. J.: 'A Formation Standard.' TAPPI **41**, 4, 212. April, 1958.

(39) Müller-Rid, W., and Pausch, G.: 'Contribution to the Problem of Water Removal from Fibrous Webs by Means of Vacuum.' Woch. für Pap. **86**, 8, 298. End April, 1958. (In German).

(40) Rodman, J.: 'A Survey of the Operating Characteristics of the Original and Latest Designs of a Suction Pick-Up.' Paper Maker International Number, p. 48. 1958.

(41) Ruch, H., and Krassig, H.: 'The Determination of Fibre Orientation in Paper.' P. and P. Mag. Can. **59**, 6, 183. June, 1958.

(42) Boadway, J. D., Friese, J., and Husband, R. M.: 'Some Studies of Research and Development Department, Consolidated Paper Corporation Ltd.' P. and P. Mag. Can. **60**, 8, T231. August, 1959.

(43) Brazington, E. S., and Radvan, B.: 'A Method of Determining the Substance over Small Areas of Paper.' TAPPI **42**, 7, 545. July, 1959.

(44) Brecht, W., Raderer, P., and Weitzel, W.: 'Tendency of Paper to Curling.' Das Papier **13**, 11/12, 237. June, 1959. (In German).

(45) Glynn, P., Jones, H. W. H., and Gallay, W.: 'The Fundamentals of Curl in Paper.' P. and P. Mag. Can. **60**, 10, T316. October, 1959.

(46) Howe, B. I. et al.: 'The Characterization of Couch Draw Stability.' P. and P. Mag. Can. **60**, 4, T99. April, 1959.

(47) Judt, M.: 'The Effect of Shake of Paper Machines on Sheet Formation and Fibre Orientation.' Das Papier **13**, (3, 4), 46. February, 1959. (In German).

(48) Judt, M.: 'The Influence of Wire Shake on the Technical Properties of Paper.' Das Papier **13**, 19/20, 483. October, 1959. (In German).

(49) MacDonald, C. E. et al.: 'Study of Newsprint Machine Wire Life.' P. and P. Mag. Can. **60**, C. 185. Convention Issue, 1959.

(50) Mardon, J., and Truman, A. B.: 'The Wake Effect, Ridge Formation and Spout Development on the Wire of a Fourdrinier Machine.' Paperi ja Puu, **4i**, 9, 391 and **41**, 10, 457. 1959.

(51) Radvan, B. and O'Blenes, G.: 'Principles of Adhesion on a Paper Machine.' TAPPI **42**, 12, 921. December, 1959.

(52) Ure, R. A., Nuttall, G. H., and 'Ad-Lignum.': 'Fourdrinier Wire Slope.' Paper Maker **137**, 4, 41. April, 1959.

(53) Attwood, B. W.: 'A Laboratory Investigation of Dynamic Drainage at Vacuum Boxes.' P. and P. Mag. Can. **61**, C, T-96. Convention Issue, 1960.

(54) Friese, J.: 'The Improvement of Paper Machine Wire Life.' P. and P. Mag. Can. **61**, 10, T-467. October, 1960.

(55) Glynn, P., Jones, H. W. H., and Gallay, W.: 'Drying Stresses and Curl in Paper.' Canadian Tech. Sec. Proc., p. 378. 1960.

(56) Howarth, J., and Banks, W. A.: 'Machinery for Automation.' Paper Technology. **1**, 3, T112. June, 1960.

(57) Ives, A. A.: 'Suction Couch Operation on Newsprint Machines.' Paper Technology **1**, 1, 43. February, 1960.

(58) MacLaurin, M. I.: 'New Instruments for Control of the Paper Machine.' Paper Technology **1**, 4, 381. August, 1960.

(59) Mardon, J., Meadley, C. K., Duchesne, J. P., and Howe, B. I.: 'An Experimental Investigation of the Problem of Breaking and Tearing of the Wet Web on the Fourdrinier Paper Machine.' P. and P. Mag. Can. **61**, 7, T-341. July, 1960.

(60) Mills, R.: 'Development of the World's Fastest and Widest Rotabelt Suction Unit.' Paper Trade Journal **144**, 18, 36. May 2, 1960.

(61) Shamolin, I. S.: 'Factors Affecting Drainage on the Wire Part.' Bumazh. Prom. **35**, 9, 6. 1960. (In Russian).

(62) Tellvik, A., and Brauns, O.: 'Studies of Table Roll Drainage.' Svensk Pap. **63**, 22, 803. November 30, 1960.

(63) Brecht, W., and Weitzel, W.: 'The Specific Cleaning action of different types of Wire Spray Pipes.' Das Papier **15**, 10a, 635. October, 1961. (In German).

(64) Campbell, J. G.: 'Simple Machine Design Changes Could Reduce Couch Breaks.' Paper Trade Journal **145**, 13, 20. March 27, 1961.

(65) Hill, V. C., and Clark, C. L.: 'Function of Flo-Vac Rotary Suction Box on Fourdrinier Machines.' TAPPI **44**, 6, 218A. June, 1961.

(66) MacPherson, R.: 'Interim Report on the Performance of Formex Fabrics on No. 2 P.M. at Laurentide Division of Consolidated Paper Corp. Ltd.' P. and P. Mag. Can. **62**, 7, T-351. July, 1961.

(67) Mardon, J., Truman, A. B., Howe, B. I., and Meadley, C. K.: 'A Review of the present state of knowledge of the Mechanism of Water Removal on the Fourdrinier Paper Machine.' Paperi ja Puu **43**, 8, 457; 9, 499; 10, 575; 11, 581. August–November, 1961.

(68) Parker, J. D.: 'Recent Theoretical Work in the Area of Sheet Formation.' TAPPI **44**, 4, 162A. April, 1961.

(69) Vercoe, J. E.: 'Fourdrinier Maintenance—Key to Machine Efficiency and Wire Life.' Paper Trade Journal **145**, 14, 36. April 3, 1961.

(70) Attwood, B. W.: 'A Study of Vacuum Box Operation.' Paper Technology **3**, 5, T144. October, 1962.

(71) Attwood, D., and Parker, J. R.: 'Basis Weight Variations Over Small Areas of Paper.' Paper Technology **3**, 5, T133. October, 1962.

(72) Emerton, H. W., Page, D. H., and Hale, W. H.: 'Structure of Papers as seen in their Surfaces.' Formation and Structure of Paper. Transactions of the September 1961 Oxford Symposium, p. 53. B.P. & B.M.A. Tech. Sec. publication, 1962.

(73) Forgacs, O. L. and Atack, D.: 'Distribution of Chemical Woodpulp and Groundwood through the thickness of Newsprint.' Formation and Structure of Paper. Transactions of the September 1961 Oxford Symposium, p. 721. B.P. & B.M.A. Tech. Sec. publication, 1962.

(74) Glynn, P. and Gallay, W.: 'Further studies on the Mechanism of Curl in Paper.' P. and P. Mag. Can. **63**, 8, T-418. August, 1962.

(75) Groen, L. J.: 'Fundamental Aspects of Filler Distribution in Paper.' Formation and Structure of Paper. Transactions of the September 1961 Oxford Symposium, p. 697. B.P. & B.M.A. Tech. Sec. publication, 1962.

(76) Hinton, A. J.: 'The problem of Two-sidedness in coloured papers.' Paper Technology **3**, 3, 229. June, 1962.

(77) Johnson, B., and Gavelin, G.: 'Investigation of Wire Wear on Swedish Paper Machines.' Svensk Pap. **65**, 22, 897. November 30, 1962. (In Swedish).

(78) Lawson, J. J. A., and Lambert, J. E.: 'Newsprint Machine Wire Life and Silicon Carbide Flatbox Covers.' P. and P. Mag. Can. **63**, 11, T544. November, 1962.

(79) Osterberg, L.: 'Transfer of Paper Webs from Press Rolls.' Svensk Pap. **65**, 6, 222. March 31, 1962. (In Swedish).

(80) Radvan, B., Dodson, C., and Thompson, A.: 'Wet End Breaks and Related Problems in operating Open Draws.' Paper Technology **3**, 3, 215. June, 1962.

(81) Robertson, A. A., and Mason, S. G.: 'Wet-end Factors affecting the Uniformity of Paper.' Formation and Structure of Paper. Transactions of the September 1961 Oxford Symposium, p. 791 B.P. & B.M.A. Tech. Sec. publication, 1962.

(82) Smith, R. T.: 'Application of the Roll-less Flo-Vac on a Fourdrinier Machine.' TAPPI **45**, 10, 830. October, 1962.

(83) Wahlström, B., and O'Blenes, G.: 'The Drainage of Pulps at Papermaking Rates and Consistencies Using a new Drainage Tester.' P. and P. Mag. Can. **63**, 8, T-405. August, 1962.

(84) Wrist, P. E.: 'Dynamics of Sheet Formation on the Fourdrinier Machine.' Formation and Structure of Paper. Transactions of the September 1961 Oxford Symposium, p. 839. B.P. & B.M.A. Tech. Sec. publication, 1962.

(85) Boadway, J. D., and Gray, J. T.: 'The Rôle of the Supporting Medium in Drainage Resistance.' P. and P. Mag. Can. **64**, 1, T14. January, 1963.

(86) Dyer, H.: 'Foils and Fabrics mean more and better Paper for Domtar.' Paper Trade Journal **147**, 15, 39. April 15, 1963.

(87) Eastwood, G. G. M.: 'A Continuous Two-Spot Formation Recorder.' TAPPI **46**, 1, 32. January, 1963.

(88) Forgacs, O. L., and Strelis, I.: 'The Measurement of the Quantity and Orientation of Chemical Pulp Fibres in the Surfaces of Newsprint.' P. and P. Mag. Can. **64**, 1, T3. January, 1963.

(89) Hendry, I. F., and Newman, J. A. S.: 'Effect of Machine Variables on the Curl of Paper.' Paper Technology **4**, 4, 381. August, 1963.

(90) Manson, D. W.: 'The Effect of Selected Paper Machine Variables on Formation.' TAPPI **46**, 8, 472. August, 1963.

(91) Prusas, Z. C.: 'Laboratory Study of the Effects of Fiber Orientation on Sheet Anisotropy.' TAPPI **46**, 5, 325. May, 1963.

(92) Redfern, A. P., and Gavelin, G.: 'A Study of Conditions affecting Wire Life.' P. and P. Mag. Can. **64**, 3, T-165. March, 1963.

(95) Schröder, S., Johnson, B., and Gavelin, G.: 'Drive Studies on Paper Machines.' P. and P. Mag. Can. **64**, 11, T-478. November, 1963.

(96) Sisler, G. C., and Maves, K. L.: 'Comparing Table Rolls and Lodding Wire Doctors.' Paper Trade Journal **147**, 8, 30. February, 1963.

(97) Lettenberger, I.: 'A Comparison of Hydrofoils with Table Rolls on a Fourdrinier Machine.' TAPPI **47**, 10, 192A. October, 1964.

(98) Svensson, O., and Brauns, O.: 'Function of Wet Suction Boxes.' Svensk Pap. Part 1: **67**, 19, 772. October 15; Part 2: **67**, 21, 860. November 15, 1964. (In Swedish).

(99) Yih, C-S., and Lin, S. P.: 'Effect of Variation of Acceleration on Free-Surface Instability.' TAPPI **47**, 2, 88. February, 1964.

(100) Abbott, E. C.: 'Practical Considerations and Results obtained from the Application of Hydrofoils to a Fine Paper Machine.' P. and P. Mag. Can. **66**, 10, T-538. October, 1965.

(101) Anon: 'New Suction Box Design and Cover Material.' Paper Trade Journal **149**, 3, 38. January 18, 1965.

(102) Clark, R. C.: 'New "Vacu-foils" provide Adjustability, High Dewatering Power.' Paper Trade Journal **149**, 25, 52. June 21, 1965.

(103) Descary, I. G.: 'Dominion Adjustable Foils.' P. and P. Mag. Can. **66**, 12, T-611. December, 1965.

(104) Doane, F. P.: 'The Use of Synthetic Forming Fabrics on Fine Papers.' P. and P. Mag. Can. **66**, 6, T-313. June, 1965.

(105) Roecker, A. C.: 'Evaluation of Fourdrinier Foil Designs.' TAPPI **48**, 7, 109A. July, 1965.

(106) Schröder, S., and Svensson, O.: 'The Influence of Efflux Ratio on the Properties of Paper.' Svensk Pap. **68**, 2, 25. January 21, 1965. (In Swedish).

(107) Svensson, O., and Brauns, O.: 'Forming Boxes increase Production and improve Quality.' Paper Trade Journal **149**, 14, 38. April 5, 1965.

(108) Svensson, O., and Osterberg, L.: 'Function of Wet Suction Boxes.' Part 3. Svensk Pap. **68**, 11, 403. June 15, 1965. (In Swedish).

(109) Thorp, B. A.: 'Hydrofoil Design and Application is an Evolving Science.' Paper Trade Journal **149**, 2, 37. January 11, 1965.

(110) Dushnicki, T. S.: 'A Laboratory Investigation of the Effect of the Drainage Forces on Wire Mark.' P. and P. Mag. Can. **67**, 8, T-356. August, 1966.

(111) Hanson, V. E.: 'Control of Wire Table Drainage—Foils show Versatility.' Paper Trade Journal **150**, 52, 34. December 26, 1966.

(112) Luhde, F.: 'The Effect of Wire Speed and Dandy upon Sheet Formation and Wire Mark.' P. and P. Mag. Can. **67**, 9, T-381. September, 1966.

(113) Manson, D. W., and Gillis, R. C.: 'Effect of the Fourdrinier Shake on Formation.' P. and P. Mag. Can. **49**, 10, 2A. October, 1966.

(114) Mardon, J. *et al.*: 'Free Surface Flow for Papermaking.' P. and P. Mag. Can. **67**, 7, T-314. July, 1966.

(115) Norman, R. J.: 'Dependence of Sheet Properties on Formation and Forming Variables.' Consolidation of the Paper Web. Transactions of the September 1965 Cambridge Symposium, p. 269. B.P. & B.M.A. Tech. Sec. publication, 1966.

(116) Page, D. H., Sargent, J. W., and Nelson, R.: 'Structure of Paper in Cross-Section.' Consolidation of the Paper Web. Transactions of the September 1965 Cambridge Symposium, p. 313. B.P. & B.M.A. Tech. Sec. publication, 1966.

(117) Radvan, B., Dodson, C., and Skold, C. G.: 'Detection and Cause of the layered Structure of Paper.' Consolidation of the Paper Web. Transactions of the September 1965 Cambridge Symposium, p. 189. B.P. & B.M.A. Tech. Sec. publication, 1966.

THE PRESS SECTION

INTRODUCTION

4I In one of the early classical text-books on papermaking the press section is dismissed in just under one page, and part of that is covered by a photograph of a typical old plain straight-through press. It is only in comparatively recent times that this neglect of the presses has been remedied and during the last few years a considerable amount of research has been devoted to this essential part of the Fourdrinier. Normally the press section provides little trouble to the machine operators, at least once the sheet has been successfully threaded through, and apart from attending to the condition of the wet felts and seeking to remedy the occasional wet streak which can be attributed to the press operation very little attention is required or given. The pressure applied in the presses is frequently kept the same for long periods once a new wet felt has been run in, and alterations are then more frequently to relieve pressure than to apply more.

Except in the rare case where some restriction to the quantity of steam available for the drying cylinders puts a limit on production and highlights the importance of running the paper leaving the presses as dry as possible, the desirability of this objective is rarely in the forefront of the operator's mind. One of the reasons for this is undoubtedly the difficulty of assessing at all accurately whether the press is functioning as efficiently as it might. An excessive demand for steam is one indication that the moisture content entering the cylinders is too high but, except on some machines with hoods and an efficient controlled air recirculation system, there are many other factors which can alter steam requirements; in particular, the moisture content of the paper at the reel-up is important though usually it is not easy to keep a close check on this property. Changes in press performance which are not due to definite malfunctioning are all fairly gradual in nature and this increases the difficulty of keeping a high efficiency of water removal by visual observation. Alterations over a period of the pattern of water throw-out from the shell of a suction press or the flow of water from the press trays are not of a nature to cause the operator to take any action until they become very obvious.

Yet the efficiency with which a press removes water is by far the most important criterion for assessing performance. The properties of paper can alter very slightly as a result of pressing under different conditions, but not to an extent which is usually of any great importance in the manufacture of most grades, at least within the normal variations in running found on presses. Indeed the precise effect of wet pressing is the subject of some difference of opinion. Generally it has been thought that as a result of the promotion of fibre bonding under pressure, bulk is decreased and strength and smoothness increased in pressing. But recent work (57, 58) indicates that although consolidation of paper structure takes place it may

303

in some circumstances be due to the collapse of individual fibres which could damage bonds already formed and produce a reduction in strength properties. The response to press loading appears to depend on the strength of bonds already formed, the relative intensity of local hydraulic pressure in the nip, and on the deformation characteristics of the individual fibres involved. Other work (54) has indicated that reduction of bulk is greater when the same solids content entering the dryers is achieved as a result of three separate presses working at a lower linear pressure instead of two with a high linear pressure. Also, it was observed that although smoothness improved on the top side of the sheet it was impaired on the wire side due to felt mark.

In practice the only noticeable effect of the presses on quality is when excessive pressure causes structural deformity in the sheet and leads to crushing. At loads slightly under the crushing point deterioration of quality occurs as fibres are washed out and re-aligned in the press nip, but when the crushing point itself is reached the web stretches and eventually folds over into creases and breaks up. Up to the point where these adverse effects are apparent, increasing the load in the presses has most influence in improving the efficiency of water removal. But there are, of course, many other factors affecting press efficiency and it is proposed to discuss these in some detail so that their relative importance to any particular application can be assessed more easily.

4I.1 Importance of dryness leaving the presses

It cannot, however, be stressed too much that obtaining as dry a sheet as possible leaving the presses consistent with keeping up the quality of the paper is one of the machine operator's most important tasks. This applies not only to the average moisture content of the sheet but also the evenness of the moisture profile; a section across the sheet which is wetter than the rest of the web entering the cylinders will almost always show up damper at the reel-up and the dryerman will then control his reel-up moisture content to that part of the sheet and dry down the rest of the sheet more than is necessary.

As an approximate guide, the cost of drying an equal weight of water in the cylinder section of a paper machine is usually quoted at about seven to ten times the cost in the presses, though this of course depends a great deal on the relative steam and power costs and the efficiency of heat usage. In several text-books graphs and tables show that if, for example, the water to fibre ratio of the paper leaving the presses increases by one third from 1·5 to 2·0, then the approximate steam consumption changes from 2·0 to 2·7 lb. steam per lb. paper, which is also an increase of almost one third, the slight discrepancy in the calculation being due to allowance for water left in the sheet at reel-up. In fact these figures are derived from average conditions and the degree of change in steam consumption is too pessimistic because it does not take account of two important considerations. Firstly, a proportion of the steam used on any machine serves only to balance heat losses in the system and is not used to evaporate water from the sheet;

secondly, less heat is required to remove water in the sheet when it is relatively damp than when it is almost dry, so that moisture added due to press inefficiency does not need an exactly proportional increase in heat to remove it in the drying section. A more realistic picture is obtained if it is considered that additional steam usage is one half to two thirds that of the theoretical figure derived from a simple proportional calculation based on the percentage increase in water/fibre ratio at the press in the manner mentioned above. Nonetheless when the relative costs of the water removal are taken into account it is still at least five times as expensive to dry additional moisture in the drying section than to remove it in the presses.

4I.2 Representation of moisture figures

Before commencing a description of the theory of pressing it is worth noting the importance of quoting moisture figures at the press, as on the wire, in terms of water to fibre ratio. Too often results are quoted in the form of percentage moisture or dryness figures, although these do not convey the degree of change in the actual water content of the sheet adequately. To illustrate this point consider the table below which covers the usual range of moisture values applicable to the press section:

Moisture content %	Dryness %	Water/fibre ratio
85·7	14·3	6
83·3	16·7	5
80·0	20·0	4
75·0	25·0	3
71·4	28·6	2·5
66·7	33·3	2
60·0	40·0	1·5
50·0	50·0	1

For a unit change in the water/fibre ratio, and hence in the quantity of water remaining to be removed from the sheet, the moisture content percentage alters appreciably less the higher the water/fibre ratio, i.e. the wetter the sheet, and this confuses assessment of press performance. Moisture content figures are preferably confined to the reel-up and drying section where they are more useful and representative of the properties of the paper.

CHAPTER 4A
GENERAL THEORY OF PRESSING

4A.1 EARLY THEORY

An interest in discovering precisely what happens in the nip of a press has, in common with interest in other parts of the machine, been stimulated in post-war years by the general increase in machine speeds. Press performance has been observed to fall off as higher speeds have been attained and research has been directed to discover why. In addition the felt manufacturers, anxious to keep up and improve their products in the face of these increasing speeds, have devoted time and money in an endeavour to determine the precise rôle of the felt in the press. The culmination of this interest came in 1960 when the publication of a paper by Wahlström (21) completely overturned the theory that was generally accepted as describing the operation of a press. Since then a great deal of confirmatory evidence has been published and Wahlström's theory must be accepted as approximating closest to experimental observations. The comparative newness of the theory and the controversy that preceded its appearance makes it desirable to give a fair, if brief, recapitulation of the old theory first.

4A.1 1 Nissan's theory of pressing

The theory that held favour up to recent years was propounded most fully by Nissan (5). Within the ingoing side of the press nip the compression was assumed to close up and saturate the felt causing water to be expressed from it either back out of the nip in the case of a plain press or into the holes in the case of a suction roll press. The main function of this part of the nip was to remove the water carried round by the felt; apart from a small compression of the paper, little or no water was imagined to leave the sheet which was almost as wet at the centre of the nip as when it entered the press. Within the outgoing side of the nip the gradual relaxation of pressure allowed the felt to expand and this action was envisaged as providing a suction force drawing water from the paper to the felt and to be responsible for removing the greater part of the water from the web.

The consequences of this theory are that it appeared desirable to have a felt which was as compressible and elastic as possible, as well as being permeable through the thickness of the felt and along the length. The felt should, in fact, be bulky and possess large interstices compatible with not marking the paper. As the water was removed from the web essentially by being sucked into the felt in the outgoing side of the nip it would be preferable for this to take place over as long a time as possible, which implied a wide nip width and allowing the paper and felt to remain in contact as long as possible.

306

4A.1 2 Observations of Osborn and Wicker

There were certain aspects of this theory which did not seem quite to fit observations of the press section. As early as 1956 Osborn and Wicker (7) had published the results of an interesting investigation in which a beta ray gauge was used to determine the moisture in a first press felt while it was running on a paper machine. When increasing the total load on the press they discovered, as expected, that a greater quantity of water was removed from the press roll tray. But also it appeared from the beta ray gauge measurements that the felt carried round less water as the nip pressure increased. The relevant graphs showing the variation between the water removed and the percentage of water in the felt as the nip pressure altered are shown in Figs. 4.1 and 4.2.
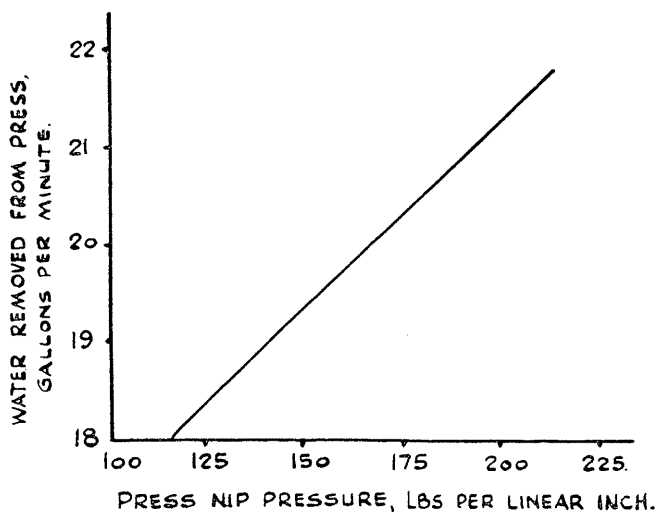
Fig. 4.1. Relation between water removal and nip pressure (after Osborn and Wicker)

Although Osborn and Wicker made no comment in their paper, the theory current at that time could not satisfactorily explain the decrease in water carried round by the felt as the nip pressure increased. If suction of water from the paper to the felt in the outgoing side of the nip were the primary cause of water removal it would be expected that when more water was extracted from the web into the felt due to the increased pressure this additional water should either have no effect or lead to an increase, not a decrease, in the water content of the felt. It is possible to elaborate the theory to explain this discrepancy, but a straightforward application of the theory undoubtedly leads to a contradiction.

Another observation made in the same experiment was also unexpected. When a break occurred and paper stopped passing through the press nip, the moisture content of the felt was observed suddenly to increase by about

2·5 per cent. If the felt were extracting water from the web in the outgoing side of the nip and the water was suddenly not there to be extracted, it is evident that the moisture content of the felt should decrease. Osborn and Wicker sought an explanation of this phenomenon in terms of the reduction of suction press vacuum (from 10 in. Hg. to 5 in. Hg.), which occurred at the same time due to a greater air flow through the felt when the paper was no longer present to seal it. This, they argued, would result in less effective retention of the water by the suction roll and consequent partial rewetting
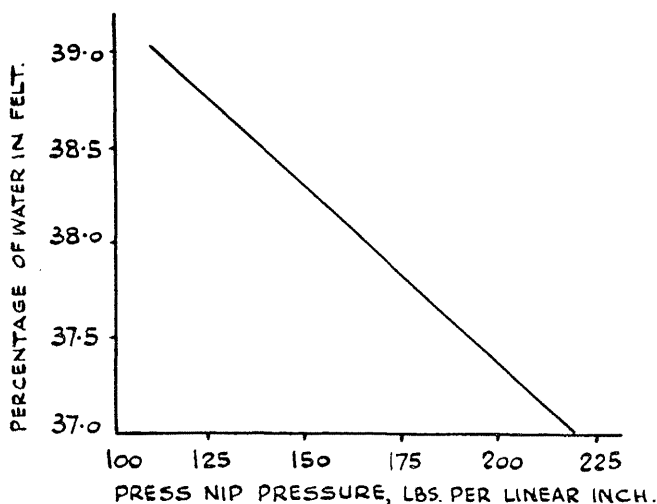
Fig. 4.2. Relation between moisture content of felt and nip pressure (after Osborn and Wicker)

of the felt as it emerged from the nip. This explanation is now known to be incorrect mainly because, as will be seen later, alteration of the vacuum of a suction press has relatively little effect on water movement in the holes of the press roll.

4A.13 Experimental work by Sweet

One further set of experimental observations although not published until after Wahlström's paper appeared were known to him and provided evidence completely contradictory to the old theory of pressing. This work has been described by Sweet (26) and involved the use of an experimental press. Sheets of paper were made up from a varying number of layers of thin wet sheets of tissue and these were passed through the press with different felts. The reduction in moisture content of the paper resulting from the pressing was determined. Under any particular set of press conditions and with the same felt, increasing the number of layers which comprised the sheet, i.e. the thickness and substance of the sheet, always up to a certain point resulted in the pressed sheet having a lower moisture

· content. Figure 4.3 illustrates a typical result. In other words the thicker the sheet, despite the greater quantity of water entering the nip in the paper the more water proportionally was pressed out. If water were removed from the sheet by suction in the outgoing side of the nip it is impossible to explain why the presence of a thicker sheet should cause so much more water to be removed that the sheet emerged at a lower moisture content than it would were it thinner.

The only explanation of this unexpected result is that water is removed from the paper in the ingoing side of the nip and reabsorbed in the outgoing side. The volume of water removed when entering the nip would
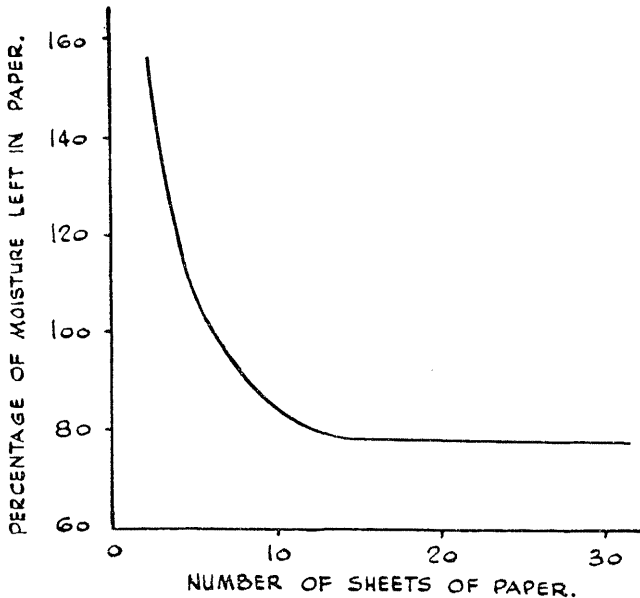
Fig. 4.3. Relation between moisture content and number of sheets of tissue passed through an experimental press (after Sweet)

appear, given the same nip conditions, to be fairly dependent on the thickness of the paper, so that the moisture content at mid-nip is always the same, whereas the volume of water absorbed on leaving the nip remains fairly constant irrespective of the thickness. The water reabsorbed thus influences the ultimate moisture content of the sheet to a more prominent degree when the sheet is thinner because it then represents a greater quantity in relation to the volume of water carried by the sheet.

As the reabsorption in the outgoing side of the nip appears to be relatively independent of the paper thickness it may be deduced that it is a surface phenomenon involving transfer of water from the felt surface into the sheet. One way of checking this hypothesis is to see what is the effect

of using two wet felts, one on either side of the paper, since this would allow reabsorption to take place on both sides of the paper. An experiment for this purpose is reported by Sweet and involved comparing the final moisture content of the sheet, made up of varying layers of tissue as before, under two conditions; in the first case the paper was run through the press sandwiched between two wet felts and in the second case the same two wet felts were placed together on the underside of the paper. In this way the press nip conditions were kept the same but the paper was con-tacted by a felt first on both sides and then on only one side. The result of this elegant experiment confirmed that water is transferred from the felt to the paper when leaving the nip. In every case, whatever the thickness of the sheet of paper, the moisture content after pressing was significantly higher when the paper was sandwiched between the felts.

Other experiments are reported by Sweet and in every case evidence of the transfer of water was observed. A similar result was found by White and Berdux (22) using a static press when it was observed that migration of water from felt to paper occurred when pressure was released. With the evidence that has been described, coupled with considerable work of his own, Wahlström put forward a new explanation of pressing which will now be described.

4A.2 MODERN THEORY OF PRESSING

As paper and felt enter the nip of a press a gradual compression between the press rolls occurs. The paper, being more saturated with water than the felt, can compress only to a relatively small extent. Most of the compression which takes place up to the nip centre occurs in the felt as it compacts with the removal of air from its structure. From the point where compression commences up to nip centre a gradually increasing pressure is exerted by the press rolls. First, consider the situation at a point within the nip where the gap between the two rolls has narrowed sufficiently to exert a com-pressive pressure on the felt and paper.

4A.2 1 Transfer of water from paper to felt within ingoing side of press nip

At any particular point within the nip if an imaginary line is taken across the machine parallel to the rolls then the thickness of the nip, i.e. the gap between the rolls, must be the same all along the line and the paper and felt together must be compressed to the same extent. The pressure applied by the rolls must be identical at each point along this line and must be balanced by an equal and opposite pressure in the felt and paper. A section through the felt and paper along this line would be subject to the same pressure all over it, in exactly the same way that a horizontal section through a tank of water will also have a uniform pressure acting on it. Passing further into the nip is equivalent to going lower down in the tank though in the case of the press rolls the rate of change of pressure with change of position through the nip is not uniform, but is greater at the point of entry where the distance between the rolls is narrowing most rapidly.

Returning to the imaginary section, it has been stated that the roll pressure is balanced by an equivalent pressure within the felt and paper. This pressure comes from two main sources: the force required to put the felt into compression (analogous to the force needed to push down a spring) and the hydraulic force which comes from subjecting the water in the felt and paper to pressure. Throughout the section the sum of the compressional force and the hydraulic force must be the same and be equal to the pressure exerted by the rolls. Although the sum of the two forces must be the same this does not, of course, mean that the individual compressional and hydraulic forces in the felt and the paper should be the same; it is precisely the difference between the relation of hydraulic to compressional forces in the paper and felt that is important.

The paper enters the nip fairly close to saturation. As pressure through the thickness of the paper increases a small amount will be used to overcome compression resistance, but as the paper passes further into the nip by far the majority of the pressure increase will cause the hydraulic pressure of the water in the paper to build up. By comparison the felt is far from saturation on entering the nip; the pressure it encounters will be used up much more in overcoming the compressional resistance required to close up and saturate it and only towards the centre of the nip will the hydraulic pressure of the water in the felt begin to grow. It is evident then that shortly after entering the nip, when the paper approaches saturation, there will be an increasing hydraulic pressure difference between the paper and felt. This pressure difference will, against capilliary resistance in both fabrics, produce a flow of water from the paper to the felt. Further the magnitude of the pressure difference must grow at least up to the point where the felt also becomes saturated. After this point is reached it may remain fairly steady or alter slightly depending on the small additional pressure absorbed by further compression of both fabrics.

The precise relationship governing the difference between the hydraulic forces in the felt and paper and the resulting water movement between them are difficult to characterize in any detail. They must depend on many factors beside the relative water content of the two fabrics entering the press and the extent to which they may be compressed; in particular the change in porosity that occurs with compression and the movement of water itself will have an important influence. It is reasonable to deduce that, other things being equal, the final magnitude of the hydraulic gradient between the paper and felt in the region of the nip centre is a crucial factor and this implies that the greater the pressure at that point the more water will be expressed into the felt. Thus, for a given load on the presses it should be preferable to have a short nip width in order to distribute the load over a small area and achieve maximum pressure at nip centre. Where the same pressure at the centre of the nip can be achieved with a wider nip by greater loading, this would be expected to be better because the hydraulic gradient will have operated for a longer time and therefore will have been able to pass through a greater quantity of water. These aspects of the theory will be discussed in more detail later when experimental evidence is produced, but it may be noted that the traditional representation of

pressure in the presses by relating the total load to the length of the nip is not sufficient to define the influence of load on the performance of the press.

4A.2 2 Removal of water from felt within ingoing side of press nip

So far discussion of the forces operating at the ingoing side of the nip has been confined to those acting through the thickness of the felt and paper. These forces lead to the movement of water from paper to felt. But a pressure gradient also exists along the width of the nip directed from nip centre back to the position where compression starts at the entry to the nip. It is this gradient which is responsible for removal of the water from both fabrics. The flow of water back out of the nip must be almost entirely through the felt and under a given pressure gradient must be governed entirely by the resistance encountered. The velocity of the flow relative to the felt must be greater than the machine speed in order that water can move backwards relative to the press rolls, so it is immediately obvious that increasing machine speed, with all other factors constant, will lead to a reduction in the water expressed at the nip.

With a plain press water must flow through the felt over the whole distance from nip centre to the point of entry before it can escape and therefore has to overcome a high total resistance to flow through the felt. The resistance to flow in a lateral direction is known to be smaller than through the thickness of a felt so that water expressed from the paper into the felt should not meet a build-up of resistance on this account. But it is clearly desirable to use a felt which, even under compression, has a high lateral porosity along its length. In addition, other factors being equal, a short nip width would reduce the total resistance to water flow through the felt.

The essential advantage of a suction press at the ingoing side of the nip is to reduce the distance water must travel through the felt before it can escape. With increasing machine speed this advantage is extremely important because on a plain press the felt reaches the stage of being completely clogged with water and a pond forms in the nip. The movement of water through the felt in a suction press is not easy to define because the pressure gradient along the nip will be modified by the presence of the holes. Over the holes there must be an area of lower pressure than at a corresponding position parallel to the roll axes over a land area. Hence some movement of water will occur across the machine. At all events it can be seen that the distance between holes along the circumference of the suction roll is very important and it is desirable to keep this distance as short as possible. It is also apparent that the lower pressure over the hole areas and the flow of water into them from surrounding land areas, particularly from the side of the hole facing towards nip centre, will cause the felt to be wetter over the holes. The paper will also be wetter over the hole areas at nip centre because the pressure at that point, which has been seen to be important in determining the water flow from paper to felt, will be lower than in the

surrounding land areas. These points will be reconsidered when shadow-marking is discussed later.

4A.2 3 Summary of desirable conditions within ingoing side of press nip

Before considering the second phase in the outgoing side of the nip it will be useful to summarize the characteristics which, on the basis of the theory propounded, appear to be desirable. Two objects have to be achieved: (i) as much water as possible must be forced from the paper to the felt by having as high a hydraulic gradient as possible acting for as long a time as possible, (ii) the total resistance to flow of water through the felt to a region where it can escape must be as low as possible. This requires:

1. High pressure at nip centre.
2. Felt dry entering nip.
3. Felt porous under pressure, particularly along its length.
4. Felt relatively incompressible.
5. Hydraulic gradient from paper to felt acting for a long time.
6a. In plain press, nip width small.
6b. In suction press, distance between holes along circumference of roll small.

Some of these requirements are incompatible. The load that can be applied to any press is limited and, if this limit is approached in operation, 1 can only be achieved with a shorter nip width which affects 5 adversely (although in fact the time factor may not be so important). In a plain press a short nip width is desirable for removing the water on another score, 6a, so considerations in this case point to the preference for features contributing to a short nip such as hard rubber-covered rolls which are small in diameter compatible with the requirements of structural rigidity. For a suction press the same features are also desirable though not to quite the same extent. It is difficult to make a felt which satisfies both 3 and 4 at the same time. What seems to be ideal is an open felt which requires a substantial force to compress it. This would contribute to keeping a short nip width and, by absorbing the roll pressure in compression, would allow the hydraulic gradients to build up while at the same time offering only a small resistance to movement of water in the felt. It may also be noted that in a second press where the paper is more dry and compressible each of the requirements detailed above will be relatively more important, especially 2 and 4.

4A.2 4 Conditions within outgoing side of press nip; shadow-marking

Passing through the centre of the nip the pressure on the felt and paper is gradually relieved. In this phase of the nip, water is drawn back into the paper from the felt largely by capillary attraction. Tests on a variety of felts and papers indicate that the average capillary size of the paper is always smaller than that of the felt so that there is ample evidence that a force would operate across the felt/paper surface drawing water out of the felt. At the same time, as the fabrics expand air/water intersurfaces will be formed,

mainly in the felt, and water will redistribute into the smaller capillaries. This will also draw a certain amount of the water adhering to the surface of the felt over the holes of a suction press back into the felt.

In a suction press the amount of lateral as opposed to vertical redistribution of water which takes place within the felt and paper is difficult to determine. One school of thought inclines to the view that very little redistribution occurs; the paper and felt becomes wetter over the hole areas largely because the pressure in the nip is lower in those regions and also, in the case of the felt, because of the flow of water through the felt to the holes. A second school believes that the felt, and in turn the paper, becomes wetter over the hole areas mainly because of the water reabsorbed from the holes in the outgoing side of the nip; redistribution of water from hole to land areas in the body of the felt prevents the difference in moisture from becoming excessive.

Questions concerning the extent of lateral redistribution of water from hole to land areas and the amount of reabsorption of water from holes in the outgoing side of the nip are important principally in connection with shadow-marking. It has been thought for some time that the basic cause of shadow-marking is attributable to differences in moisture content of the web over land and hole areas as it leaves the roll. But the reason this difference persists through to the finished paper has not been clear.

Work reported by Redfern and Gavelin (32) has now indicated that shadow-marking is due basically to the difference in pressure experienced by the paper over the hole and land areas of the shell. They detected a significant difference between the structure and density of the sheet in the two areas and demonstrated the existence of a slight plastic flow of fibre from the land to the hole areas. It appears that a difference in the degree of fibre bonding between the two regions of the sheet occurs due to differences in compression in the nip and it is this, rather than the difference in moisture content of the sheet over the hole and land areas, which is considered responsible for producing shadow marks in the finished paper. The hole areas in fact appear lighter than the land areas due to the difference in light reflection caused by the lower number of bonds.

Shadow-marking often becomes troublesome mainly when a felt is drawing near to the end of its life, and it is precisely at this time, when the felt has become hard and plugged, that the difference in pressure over the hole and land areas will be accentuated. Relieving the load on the press or using softer rubber-covered rolls will help to reduce the difference in pressure but both must be considered retrograde steps since they will reduce press efficiency. Redfern and Gavelin consider that the only feasible measure against shadow-marking on an existing press, which need not at the same time reduce efficiency, is to use a different type of press felt that is stiff enough on the underside not to be pressed into the holes.

4A.2 5 Reducing rewetting of paper in the outgoing side of press nip

It will be appreciated that while extraction of water in the ingoing side of the nip is largely independent of paper thickness, reabsorption in the

outgoing side of the nip, being a surface phenomena, will affect both thinner and drier paper to a greater extent. If the quantity of water flowing over the felt/paper surface is relatively constant it will raise the moisture content to a proportionally greater extent when there is less water already in the paper. Thus, prevention of rewetting will be of greater importance in a second press. The evidence for this transfer of water already quoted in the work of Osborn and Wicker and of Sweet was confirmed by Wahlström when he observed that the water carried round by the press felt increased with paper no longer passing through the nip. In addition he observed that without paper passing through the nip the top roll was wetter and this supports the view that capillary attraction is less in the felt than the paper.

The transfer of water from felt to paper in the outgoing side of the nip will be kept to a minimum by having:

1. Short nip width to reduce rewetting time.
2. Quick separation of paper and felt.
3. Small felt capillaries, particularly at surface contacting paper.

The third requirement is partially contradictory to the desirability of having an open felt which has been shown to be preferable for the ingoing nip phase. This emphasizes the difficulty of obtaining an ideal felt and the necessity for compromise in felt properties to produce the most effective type for assisting water removal.

These considerations have led to the idea that a more efficient press arrangement would come from separating the two functions of absorbing water from the paper and then removing it from the felt. For the first function a felt can then be used which is thick and heavy enough to absorb all the water expressed in a plain press nip without attempting to pass any water out of the nip for removal. The felt, carrying all the expressed water with it, then enters a separate high-load press or some other method designed to remove most of the water it contains. The means adopted for water removal from the felt can be much more drastic than is possible where paper is present, and the felt should enter the main press nip relatively dry.

The effectiveness of such an arrangement must depend on the degree of rewetting which occurs on the outgoing side of the nip compared to the ability of the felt to absorb all the water removed from the paper. That rewetting has a fairly minor influence in comparison with the ability to remove water from the web has been suggested by the work of Robinson (43) and Swanberg (45) who have both demonstrated that the use of two felts, with the web sandwiched in the middle in a 'double-divided' press, gives superior operation.

Robinson, on a machine making an extremely wet-beaten transparent paper and equipped with five plain presses, made a modification in such a way that one of the presses could be missed and used instead for dewatering a second felt added to an adjacent press. Two different arrangements like this were tried and in each case there was an appreciable improvement in the overall efficiency of the press section. Swanberg adapted a conventional

suction press and bottom felt arrangement to incorporate a top felt and wringer rolls; in a later experiment a fabric felt was also added between the top felt and top roll. Under practically all operating conditions (speed above 300 f.p.m., substance above 50 g.s.m., freeness above 20° S.R.) the first of these arrangements gave improved water removal at all linear nip pressures compared to the conventional set-up, while addition of the fabric felt improved removal even further. It would appear from this work that under conditions where the web is dewatered from both surfaces the resultant increase in pressing time and lower resistance to water flow from the web can be more important than the maximum hydraulic pressure achieved in the centre of the nip (since this will be lower for two felts compared to a single one). Secondary advantages of the double-felt arrangement are the absence of any adhesion to the top roll, which can be particularly troublesome with some grades, and reduction of shadow-marking for the same load on the press.

4A.2 6 Recent developments

Coincident with and as a consequence of the findings of Wahlström there has been a considerable development of press section design culminating in recent years in several new arrangements appearing on the market. Each has been developed in an endeavour to overcome the shortcomings of the normal plain press design without incurring the high cost of suction press rolls and pumps. They have generally been installed in second press positions where there is more scope to improve efficiency, and represent in different ways attempts to reconcile the need to attain higher nip pressures (in order to express more water from the web into the felt) with the ability to allow the water expressed to escape from the felt without building up a high hydraulic pressure leading to crushing. Not all have yet proved fully operational, though several arrangements are now used in sufficient numbers to warrant mention.

The first of these is the fabric press which incorporates a specially designed, incompressible, fine open mesh, plastic fabric running between the felt and the press roll (33, 34, 35, 46). Water absorbed by the felt is pressed into the fabric and subsequently thrown out as the fabric separates from the roll, or is sucked out at a suction box. The fabric requires its own guide and stretch rolls, and a camber bar or expander roll to keep it taut across the width of the machine. An adaptation of this is the sleeve press in which a fabric equal in length to the circumference of the roll is shrunk onto the roll (48, 49). Reports on these two arrangements have indicated improvements in dryness leaving the press compared to both plain and suction presses of conventional design. Each can be used in conjunction with an existing suction press and this gives an even greater improvement in overall efficiency and can be useful to overcome a severe shadow-marking problem. There are also indications that the use of a fabric press with high load can improve strength properties at the expense of a reduction in bulk and air resistance (54).

A second arrangement, known as the Venta-nip press, utilizes a 10 to 30 thou wide spiral grooving in a plain bottom roll. This assists removal of water from the felt and allows greater nip pressures than could be used with a plain roll; water is removed from the grooves by a type of foil followed by a doctor (a low vacuum may be applied between the two for speeds under about 700 feet per minute), assisted at higher speeds by centrifugal force (when only a doctor is necessary) (39). Reports on this type of press are fewer but several are known to be working successfully, giving improved dryness even compared to a suction press. Problems in their use appear to be mainly concerned with obtaining a satisfactory design and life for the clothing and also, in some applications, with keeping the grooves clean.

A third innovation is the Hi-I press which involves the use of a small diameter, stainless steel, grooved roll which runs in the nip between the two principal press rolls in such a way that it lies between the felt and a roll. It is claimed (56) that nip pressures three times greater than normal are possible with this arrangement and this gives an exceptionally high improvement in press efficiency. Several installations are now in operation. Other modifications in the process of development include use of an impervious belt running from the wire into the first press nip, and of a special type of porous nylon material covering a perforated steel press roll which allows water expressed from the web (possibly without any felt in the nip at all) to pass into the body of the roll. Preliminary laboratory tests have confirmed the advantage of using this latter material (42), but there have been no reports of a full-scale operating application.

OPERATING FACTORS AFFECTING PRESS PERFORMANCE

4B.1 PRESS LOAD AND NIP WIDTH

The influence of nip pressure on water removal and on the moisture content of the felt has already been mentioned in 4A.2 1. Experimental work shows that the felt has less moisture in its body the higher the nip pressure, and it was seen that this is one of the pieces of evidence favouring the new press theory. The general relation between water removal and nip pressure obtained by Osborn and Wicker and shown in Fig. 4.1 has been confirmed under different conditions by several other workers (2, 10, 21) and is familiar to all papermakers. Alteration of the press load is probably the most important variable on a press and all the experimental curves show that the moisture content of paper leaving a press is closely dependent on this. There is evidence that greater nip pressure affects bulk and strength properties, see 4I. A greater nip pressure also appears to reduce the life of a felt (17) and will increase the power required to drive the press.

4B.1 1 Importance of nip width

The pressure in a press nip is customarily quoted in lb. per linear inch because of the difficulty of obtaining an accurate measurement of the width of the nip especially under operating conditions. Even if the force exerted were related to the area of the nip to obtain a more conventional pressure figure it is evident that the result obtained would give only an average value since the pressure is not evenly distributed over the nip area but is, of course, much greater at the centre of the nip. Nevertheless Wahlström has found that the figure for pressure obtained by relating the force applied to the area of the nip (and termed by him 'specific nip pressure') bears a closer relation to water removal than pressure measured at lb. per linear inch. This is in accord with the theory since the specific nip pressure, by taking into account the width of the nip, gives a more accurate measure of the magnitude of the pressure at the centre of the nip and this maximum pressure is the most important factor governing the expression of water from the paper to the felt.

As water removal is dependent on the specific nip pressure it is evident that for a given load on the press the nip width is very important and the narrower the nip the more efficient will be the water removal. The upper limit for water removal on any press is when crushing occurs and shear forces in the plane of the sheet create disruption by stretching which leads eventually to disintegration of the web as it folds over in small creases in the nip (40, 47). If a press is run close to maximum load for the bearings

and there is no trouble with crushing or felt rubs then it would be desirable to attempt to narrow the nip. This could be done most easily by using a harder and more incompressible felt but it will be realized that large press rolls and softer rubber covers both contribute to producing a wide nip. When a press is run with plenty of load to spare then, up to the point of crushing, a wide nip width does not matter to the same extent, especially on a suction press.

With increasing applied load, the nip width increases slower in proportion than the load so that the specific nip pressure also increases and improved water removal takes place. A wide nip will be more noticeably disadvantageous when the paper is run between two felts as on a tissue machine or a transfer press; in this case not only will the double cushioning of the felts widen the nip but rewetting of the paper within the outgoing side of the nip will take place for a longer time in a wider nip and will occur over both surfaces of the paper. In such presses the necessity to effect transfer limits the type of felts that can be used and it becomes particularly important to be able to apply a heavy load and use relatively hard rolls if the press is to function efficiently.

4B.1 2 Experimental evidence of the influence of nip width

Wahlström obtained figures confirming the influence of nip width on water removal by assessing the effect of felt compressibility and also of the hardness of rubber on a bottom roll. In both cases with the same general press conditions the narrower nip gave greater water removal and resulted in lower steam consumption. As a felt ages and becomes less elastic and compressible the nip width decreases and this was also shown to be advantageous; this will be discussed more fully in **4B.2**.

The moisture content of paper entering the first press is considerably greater than for the second press. This implies that in the second press a greater pressure is required to compress the paper while the build-up of the hydraulic pressure providing the force for water removal will be slower. For this reason greater specific nip pressure can be attained at the second press without crushing although the effect of increasing load is not so great; Wahlström quotes a reduction of 0·04 in the water/fibre ratio through the first press as against 0·025 through the second press for an increase of 10 p.s.i. specific nip pressure on 100 p.s.i. Narrow nips are therefore of greater importance in a second press and in this respect the type of felt used is of great significance.

4B.1 3 The need to measure total press load

On most presses it is very difficult to assess nip width with any accuracy when the press is in operation. Carbon impression and other techniques such as the use of specially embossed aluminium foil permit static measurements of the nip width with and without felts but there is considerable doubt about the relation of such results to dynamic conditions. Methods involving the use of strain gauges and piezo-electric crystals have been described but are not really practicable for normal production presses.

The machine crews must rely for day-to-day operation of the press mainly on knowing the total load applied to each side of the press, yet it is surprising how many machines still have no direct measurement of this important value. Over a period the force applied by weights and levers in the older type of press can alter appreciably due to large friction losses which can build up in the system at the contact points between tension rods and lever arms and at the pivots; having the weights at the same position on each side of the press need not mean an even pressure application and machinemen often do not appreciate the difference in load produced by quite small movements of the weights along the lever arm. Likewise where springs are used their characteristics change with ageing. No press should remain unequipped with some form of load indication and on older presses devices like the Statimeter or load cells using strain gauges are extremely valuable.

Presses using air or hydraulic loading invariably have a fluid pressure gauge which is perfectly satisfactory—it is less important to have an absolute load measurement than a means of measuring the variation in load during normal operation. Whatever load measuring device is used should of course be checked and calibrated against a dead-weight mechanism at regular intervals by the instrument personnel. The relationship between the instrument reading and the absolute load applied should be known in order that the theoretical camber of the press rolls can be determined for normal operating conditions.

4B.2 FELTS AND FELT CLEANING

The function of the felt in a press, apart from conveying the paper and substituting a less objectionable felt mark for a wire mark, is to act as a conducting medium for removing water. It used to be considered that the best type of felt was one which allowed considerable compression and was sufficiently elastic to have immediate recovery; the expansion of the felt taking place in the outgoing side of the nip was believed to draw water out of the paper so that the greater the expansion, the better the water removal. The more recent press theory predicts that the best type of felt, for the first press at least, will have little compression in the nip and will be sufficiently open to retain good porosity under pressure.

These requirements have been generally verified by measuring the relative press water removal for a variety of different types of felt of a similar weight (21, 25, 30). The openness of a felt is largely determined by the weave pattern and in two separate investigations it was found that the more open reverse broken twill or chain weave was more effective in water removal than the closer plain weave. Felts which were less compressible and rather denser also gave improved water removal.

4B.2 1 First and second press felts

In the first press the paper becomes saturated after a very small amount of compression (one estimation gives the figure of 10 per cent.) while in the second press the paper will not be saturated until compression has reduced

its thickness by about half. Also, in a second press the quantity of water extracted is normally between 10 per cent. and 40 per cent. that of the first press. The requirements of a second press felt are therefore somewhat different and it would be expected that openness of the felt could be sacrificed to achieve lower compressibility. It has in fact been confirmed that denser felts with lower compressibility give better water removal in a second press than the more open felts suitable for a first press. The finer capillaries of a denser felt would also be expected to reduce the rewetting of paper in the outgoing side of the nip and this is of much greater importance than in the first press.

The felt normally carries round a quantity of water of the order of ten times that brought to the press in the paper. The hydraulic conditions in the nips are thus governed largely by the moisture content of the felt entering the nip and, especially in the second press, it is very important to keep the felt as dry as possible for efficient water removal. From this point of view it is essential when a felt is leaving the nip of a suction press to prevent any rewetting by water thrown out of the holes. Any form of cleaning device on the felt should preferably extract more water than it puts in and soft doctors on the bottom press roll preventing water being carried round to the nip have also been found effective (21). A form of suction box on the felt would help to reduce the water content where this is excessive, but the effectiveness of this must be balanced against the possibility of increased wear of the felt.

4B.2 2 Change in felt characteristics with age

When a new felt is put on a press as much load as possible is usually applied in an attempt to extract sufficient water. As the felt gets run in and becomes mechanically conditioned the load is relieved, but the water extracted will still generally be greater than initially. The process of running a felt in brings about a compaction of the felt fibres making the felt thinner and less compressible and this in itself, since it is known to improve water removal, is a good confirmation of the validity of Wahlström's theory of pressing. Also during the preliminary wetting and running-in periods there can be considerable dimensional changes in the length and width of the felt and it is one of the concerns of a felt manufacturer to assess and minimize these changes in advance and allow for them when supplying the felt.

The changes in characteristics and performance of a felt after being put on has been the subject of a certain amount of experimental work; Wahlström in his extensive paper dealt most thoroughly with this aspect and it is from his work that subsequent remarks are largely drawn. He found that throughout the life of a felt the thickness decreases and the density increases, especially in the earlier stages. At the same time the compressibility of the felt decreases and it carries round a smaller volume of water. Reduction of the compressibility corresponded to reduction of the width of the nip and to this is largely attributed the increased water removal efficiency. Fig. 4.4 illustrates some typical results on a second press felt. The increase in moisture content of the paper for a short period

immediately after start-up is attributed to the loss of water repellent material from the surface of the wool, making the felt take up more water.

The thickness of first press felts reduced and levelled off to a greater extent than second press felts and this may be due partly to differences in the type of felt and partly to differences in the quantity of water removed and carried round by the felt. The running-in period, when thickness is changing relatively rapidly, can vary from a few hours on a high-speed machine using high nip pressures to several days for lower speeds and pressures. The weave of the felt is also important and it has been found that
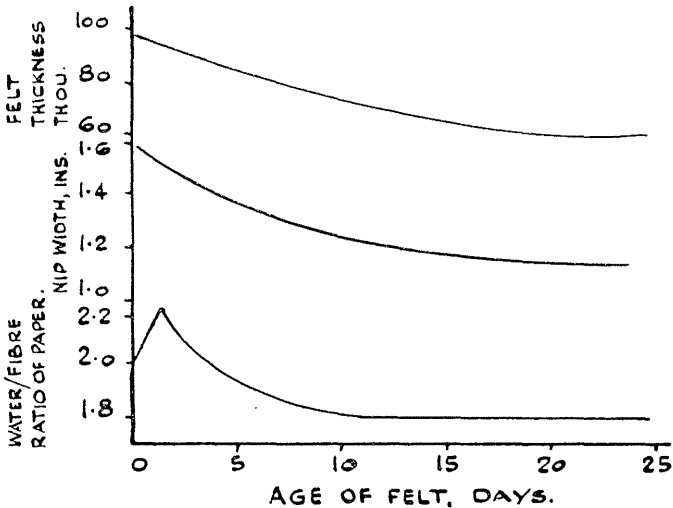
Fig. 4.4. Variation of felt thickness, nip width and moisture content of paper with age of second press felt, (after Wahlström)

the more open reverse broken twill felt reached equilibrium faster than a plain weave. With slower machines, when the running-in period is longer, the difference in time required to reach equilibrium is of much greater significance and the reduced water removal efficiency during this time becomes an important consideration.

4B.2 3 Effect of plugging in a felt

As a felt ages a certain amount of material is worn away and the dry weight of the felt is reduced. This leads to a gradual deterioration in performance and may be the determining factor governing removal of the felt from the machine. On probably a majority of machines, however, a felt is eventually taken off because it has become so hard and plugged with fibres, pitch, loading and other deposits that press efficiency has become seriously reduced; this applies particularly to first press positions. The extent of this problem varies considerably from one machine to the next.

In one investigation Peters (8) reported that he found no particular change in water removal efficiency or steam consumption during the life of felts used on a kraft machine—material filling the felt after it was removed amounted to only 1 per cent. to 3 per cent. of the total weight of the felt. By contrast on another machine making newsprint the amount of filling in the felt when it was taken off amounted to between 11 per cent. and 35 per cent. of the felt weight and in this case over the life of the felt a reduction in water removal and increase in steam consumption was observed.

Although the detrimental effect of felt plugging has long been recognized from practical experience, until recently very little headway has been made in assessing the effect quantitatively because of the difficulty of obtaining some measure of the result of plugging on felt properties while the felt is in use on the machine. Recently some success in this direction has been achieved by the use of a simple device known as the Huyck-Smith porosimeter (41). This instrument consists of a perforated disc covering a small air chamber which is held against the felt while it is running; the air chamber is kept at a constant regulated vacuum which falls as air leaks through the disc and thereby gives a measure of the porosity of the felt. The device can be effectively used for assessing differences in plugging across the width of a felt as the reading should not be unduly affected during a single traverse of the felt by calibration difficulties, variations in the pressure applied on the felt and other changing conditions.

Howe (25, 30), Wicker (36) and Delisle *et al.* (37) have also used the instrument to assess the variation of felt porosity with age and report some interesting results from this work. The measurements obtained by Howe show a steadily decreasing porosity over the whole life of a first press felt, which may be attributed at least in part to a growing quantity of material plugging the felt, while the water removal efficiency of the press gave a corresponding reduction during the same period. First press felts showed a much more prominent reduction in porosity and water removal efficiency with age than second press felts. This may be attributed to the higher flow rates in the first press and the greater removal of fines from the paper into the felts. Also it was observed that the more open the first press felt the easier it could be kept clear of filling materials; open reverse-broken twill weave felts filled to a lesser extent than denser plain weave felts. The choice of an open felt for the first press position on the grounds of obtaining high water removal efficiency will thus also help in minimizing the problem of plugging.

4B.2 4 Cleaning of felts

Recognition of the high cost in excess steam consumption due to a plugged wet felt reducing press efficiency has brought about recently a renewed interest in the question and economics of felt cleaning. Many machines do not possess any cleaning device at all on the wet felt and in this case it may be the practice to remove the felt periodically for cleaning off the machine, using a second felt while this is being done. On some machines the wet felts

may be washed and occasionally turned over at scheduled shut periods, with the felt still on the machine, or this may even be done specially in mid-week and involve stopping the machine. The relative merits of any of these methods require careful economic consideration and a time-hallowed system in use on any machine may well be completely un-satisfactory under present-day conditions. This subject will be discussed in 4C.2 1   and 4C.2 2 when attention is given to methods of supervising wet felts on a machine.

On faster machines allowing a felt to become plugged can result in a serious increase in production costs and additionally can create a great deal of trouble due to difficulties in producing a level reel. For these reasons some form of felt cleaning is in general use on faster machines. The Vickery felt conditioner has sustained a great deal of popularity and appears to be reasonably efficient even though it cleans a restricted area at any one time and also, with the exception of more recent models, gives an uneven time distribution between consecutive cleaning applications due to the design of the forward and backward traversing system. With this cleaner it is important to ensure that about the same quantity of water is removed through the suction orifice as is forced into the felt at the pressure orifice, otherwise a wet streak in the felt and paper will be observed opposite the cleaner shoe and eventually crushing will occur; this applies particularly if the felt is already well plugged.

On many machines devices cleaning the whole width of the felt are used, sometimes in conjunction with squeeze or wringer rolls; the simplest of these involves a shower across the machine followed by a full-width suction box. The width of the suction box and the vacuum applied appears to vary considerably from one mill to another, but should in practice be arranged so that as much water is extracted as is put on by the shower. An alternative to the use of a suction box, which may curtail life of a felt, is the Rolvac unit which applies vacuum to the volume formed by three rolls, two of which run in contact with the felt (the first acting as one of the squeeze rolls), the third closing the gap between the other rolls.

There have been several reports recently of the effect of using small quantities of detergent with the cleaning water, and the value of this in improving press water removal, particularly for badly plugged felts, has been amply demonstrated (8, 30, 37). The use of hot rather than cold water also keeps felts noticeably cleaner. Intermittent applications of a low concentration of detergent certainly help to prevent excessive build-up of filling material, but this procedure has been shown to have only a tem-porary effect and not to be as valuable as continuous washing with detergent (37).

To illustrate the importance of felt cleaning, the effect of starting a conditioner after leaving it off for over an hour has been examined by measuring the combined moisture and weight of a felt continuously with a beta-ray gauge (7). The weight of the moisture and filling material reduced from about 61·5 per cent. of the felt weight to 59 per cent. over a period of less than an hour, a change which would be expected to improve water removal.

When considering any new method of felt cleaning it is important to bear in mind not only the improvement in felt life and general running which may be obtained but also the effect on the water removal efficiency of the press. It is no use gaining an extra week's life for a felt if as a result the paper is running appreciably wetter to the drying section all the time. It is unfortunately very difficult to assess long-term changes in moisture content of the paper leaving the press so that a complete economic assessment is very often impossible and a decision on the merits of a change of this nature becomes more of an inspired guess.

4B.3 FELT AND PAPER RUNS

Felt runs are designed in the first place with the necessity of changing the felt as easily as possible very much in mind. Even then it is surprising how complicated some runs become and how the demands of the machine frame introduce elaborate twists and turns. For every pass round the press the amount of wear on a felt will be greater if there are more felt rolls and also the felt will be more difficult to keep square. Except on the stretch roll it is undesirable to have too severe a turn over a felt roll; although a certain degree of flexing will help to keep the felt open, an excessive amount will subject the felt to undue strain. One very important facility which is needed on a press is to be able to alter within reasonably wide limits the angles with which the felt approaches and leaves the press. This is particularly necessary with suction and transfer presses where the relative angles at which the felts and paper leave the nip can be quite critical.

4B.3 1 Conditions for a plain press

On any plain press there are two important considerations which should govern the directions of the felt and paper runs in the vicinity of the press rolls. Entering the nip it is important that bubbles of air are not trapped between the paper and felt because these will cause the paper to stretch and produce creases on either side of the bubble. Leaving the nip it is desirable to separate the felt and paper immediately to reduce the reabsorption of water from the felt into the paper.

The felt and paper will be carried together into the first press and should lap the top roll to ease water removal down the bottom roll. It is usual to couch the top roll backwards to aid the water removal. It may be necessary to have a suction box under the felt to prevent blowing, though passing the paper and felt fairly tightly over a roll at the point where they meet is usually sufficient. A suction box can be water lubricated if its operation appears to cause undue wear of the felt.

The felt should leave the first press nip lapping the bottom roll and the paper will be peeled off the top press roll. On many machines the paper is allowed to drop back off the top press roll onto the felt before transferring over to the second press felt. This should be avoided because there may be some transfer of water from felt to paper, particularly with a heavier sheet, and also creasing and rubbing can occur because the draw is not applied directly to the sheet as it leaves the first press.

The paper should be taken off the first press top roll over a lead roll (which is occasionally driven at a slower speed to reduce web slackness when the draw is long) then enter the second press lapping the top roll. The felt should also lap the top roll at a point a little nearer the nip. By pressing the paper and felt onto the top roll a certain amount of water may be transferred to the felt before entering the nip. This arrangement should prevent blowing and thereby remove the need for a suction box as in the first press. When it is necessary to support the sheet as much as possible between the presses the paper should be transferred straight
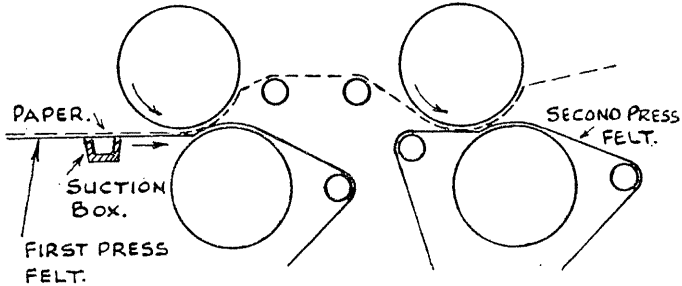
Fig. **4.5**. Preferable arrangement of runs for paper and felts through two straight-through plain presses
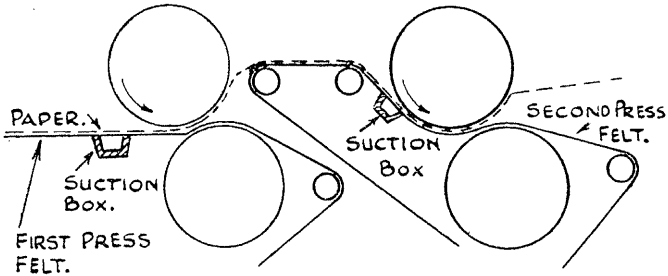
Fig. **4.6**. Runs for paper and felts through two straight-through plain presses when sheet requires maximum support between presses

from the press to the second press felt; a suction box may then be needed and then similar considerations apply as for the first press. For a reverse press the felt will carry the paper into the nip and in this case also conditions are similar to a first press. Leaving the second press nip the same considerations apply as in the first press nip. These points are all illustrated in Figs. **4.5** and **4.6**.

4B.3 2 Conditions for a normal suction press

When considering the runs for a normal straight-through suction press there are a number of different requirements to take into account; in

particular, the position of the suction box in the bottom roll is of great importance and must be considered at the same time. The leading edge of the suction box must be sealed and it would be impracticable and inefficient to ensure it is positioned actually within the width of the nip. Hence the felt and paper must both lap the bottom roll sufficiently to seal the suction box and the effect of the vacuum then serves effectively to remove air entrained between the web and felt.

In the air-bleed principle an extra wide suction box is used to allow air to be drawn through the felt before the paper contacts the bottom roll and this introduces different considerations. However, discussion of the merits of air-bleed will be left till 4B.4 3.

On leaving the nip it is equally important, as with a plain press, that the felt and paper should be separated immediately, the paper passing up the top roll and the felt lapping the bottom roll. This usually necessitates the suction box terminating at the point where the nip finishes otherwise the suction will under certain conditions tend to hold the paper to the felt instead of allowing it to pass up the top roll. To facilitate this the suction box position must be movable.

Further, the precise angle which the felt laps the bottom roll is very important in relation to the position of the trailing edge of the suction box because this determines the manner in which water in the holes of the suction press is removed. Dixon (1) first drew attention to this as a result of observations he made on a stack press and his 'pop' theory will now be described.

4B.3 3 Movement of water in suction press holes

Leaving the nip the press holes can be thought to contain a plug of water drawn from the felt by suction and to be under vacuum sealed at their outer end by the felt. The felt must not leave the roll before the leading edge of the sealing strip is reached otherwise there will be a direct leakage of air to the suction box. This is easily avoided so long as the leading edge is just within the press nip.

As the roll rotates, immediately the leading edge of the sealing strip is reached the holes in the shell are effectively sealed at both ends and still under vacuum. If now the trailing edge of the sealing strip is reached before the felt leaves the roll, air will rush in from the inside through the un-covered end of the holes and the plug of water will be driven out into the felt. This is obviously undesirable since the felt will then be rewetted. Even if the felt is removed from the roll just after the trailing edge of the sealing strip has been passed and the air pressure is equalized on both sides of the hole, the kinetic energy of the water already produced by the air pressure on the inside of the hole will still carry the water outwards, aided by centrifugal force, and into the felt.

On the other hand, suppose that the felt is removed from the roll while the inside of the hole is still sealed by the sealing strip. Air will now rush into the uncovered outside of the hole forcing the water inwards. When the inside of the hole is unsealed the air in the hole will already be effectively at atmospheric pressure and there will not be any substantial force acting to

drive the water outwards. The water will in fact leave the hole later by being thrown out by centrifugal force.

There is one remaining possibility and it is this one which was observed by Dixon and led him to consider these points in detail. If the trailing edge of the sealing strip is reached very shortly after the felt leaves the roll, the air rushing in through the uncovered outer end of the hole and pushing the water inwards will develop sufficient kinetic energy to force it to the inside of the hole just as it is uncovered. This will result in a spray directed inwards into the suction roll which is normally undesirable because it is not possible to place a tray actually inside the roll for the purpose of catching the water. This phenomenon was observed on the middle roll of a stack press where it was discovered that in a certain setting water was actually thrown upwards from the lower nip into the middle roll, a rather surprising effect.

4B.3 4 Position of felt take-off and suction box seal

It has since been proved fairly conclusively that water does not collect in the holes in the form of a plug but is in fact atomized; if the quantity of water expressed into each hole is calculated it is easily shown that it would occupy too small a volume of the hole to act as a seal across the hole. This does not, however, affect the substance of Dixon's theory since the flow of air into the holes under a pressure difference will have the same effect on water droplets as does pressure on a plug of water sealing the hole.

From the theory it is evidently desirable that the felt should leave the bottom roll at an angle slightly further round the roll than the leading edge of the sealing strip. The holes are then unsealed first on the outside where the felt leaves the roll, and air enters to carry the water inwards; by this means the eventual throw-out of water by centrifugal force is delayed as long as possible making collection of the water in a tray easier. As the sealing strip leading edge should be just within the nip, the felt will leave the nip almost directly outwards, i.e. at right angles to the plane joining the roll axes. The lead roll directing the felt off the bottom roll should be adjustable in position so that the desired angle can be set; though not too critical in most presses, the angle is obviously dependent on machine speed and, to a lesser extent, on the vacuum in the suction box.

The sealing strip should preferably be wide thereby allowing the air to reach near atmospheric pressure in the hole before it is uncovered on the inside. On some suction presses, in particular in a stack press where it may be impossible to place a tray in a suitable position, the normal suction box can be followed by a narrower box under a small vacuum designed to draw air at high velocity from the atmosphere and collect any water from the holes before it is thrown out. On most presses however the tray is positioned as close to the nip on the underside of the felt as possible to prevent rewetting of the felt from water throw-out.

4B.3 5 Ideal arrangement of suction press felt and paper runs

The normal suction press is couched forwards to allow the felt to carry the paper into the press almost horizontally and to seal the suction box in the

bottom roll at the same time. Figure 4.7 embodies the points raised above and illustrates the preferred arrangement for two straight-through suction presses. The position of the leading edge of the suction box trailing sealing strip is just within the nip and it will also be noted that the felt lead rolls after the press nip are adjustable to help in setting the correct angle at which the felt leaves the bottom roll.

On most suction presses the ideal arrangement analyzed above will be a counsel of perfection. In practice the leading edge of the trailing sealing
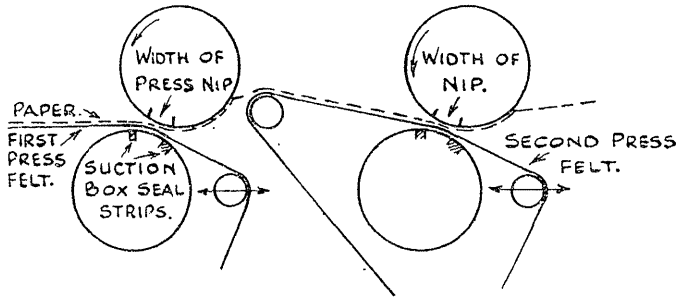
Fig. 4.7. Preferable arrangement of runs for paper and felts through two straight-through suction presses; the positions and width of sealing strips for the suction boxes are exaggerated

strip may have to be set well into the press nip otherwise variations in the width of the nip may lead to difficulties in preventing the sheet from following the felt. Especially as the felt gets dirtier and closer the paper tends to stick to the felt at the edges if the suction extends beyond the nip. It is doubtful if this will have any substantial effect on press efficiency because the nature of the capillary transfer of water from felt to paper in the outgoing side of the nip should not be affected to any great extent by continuing to subject the felt to suction. It is, though, obviously important that the suction should cover the full extent of the ingoing side of the nip since it is in this region that the water is expressed.

Likewise if the felt laps the bottom roll further round on the trailing side, provided it does not seal the roll when the suction box sealing strip terminates severe rewetting of the felt will be avoided, especially if the press tray extends as far into the nip as possible. It would appear, however, that in many cases an extension in the width of normal suction box sealing strip on the trailing side could be advantageous.

4B.36 Conditions for a press nip where paper transfer occurs

With increasing machine speeds and the desire for more compact press sections there have been in recent years a growing variety of designs embodying suction pick-up and transfer rolls, the main purpose of these being to eliminate open draws between the presses. The stack press early took this trend to its logical conclusion but it has been found to be rather

too compact and to possess several difficulties from the point of view of clothing replacement and general maintenance.

It is not proposed to discuss the merits of different press designs in any detail except with regard to the common practice of transferring from one felt to another in a nip formed by two suction rolls. Elimination of the open draw together with automatic feeding up and convenience in press arrangement are the main advantages to this arrangement although without considerably increasing the load press efficiency is reduced by the presence of two felts in the nip. Also the requirement of transferring the paper from one felt to the other tends to control the types of felt used in the different positions in preference to selecting the felts primarily for their water removing properties.

Consider the press shown in Fig. 4.8 in which the paper is transferred from the bottom carrying felt to the transfer felt on the top roll. The bottom
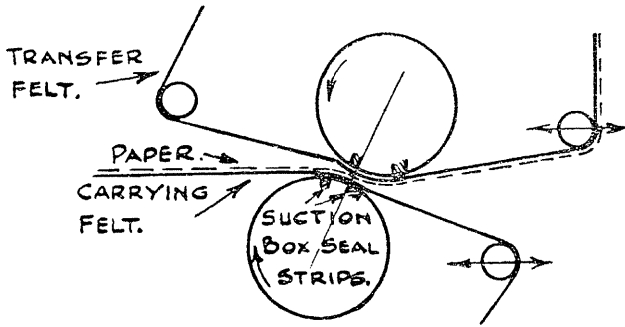
Fig. 4.8. Illustration of the preferable arrangement of paper and felt runs and position of suction boxes at a transfer press

roll would often also be the pick-up roll with a second suction box at the bottom where the roll contacts the wire. Entering the nip of the press the paper and carrying felt meet with similar conditions to those in an ordinary suction press and must be in contact with the bottom roll before the leading sealing-strip of the suction box. The transfer felt should also lap the bottom roll and cover the suction box to assist in sealing the box; further, the possibility of blowing from air trapped between the paper and the transfer felt will then be reduced because the pressure of the felt on the paper will help the air to escape upwards and out through the transfer felt.

The position and size of the bottom roll trailing suction box seal are governed essentially by the same factors that have been discussed for the case of an ordinary suction press. However, the necessity for transfer makes it particularly important that the suction area terminates well within the nip. Also in this case the bottom felt should just lap the top roll so that when it separates from the paper the underside is at atmospheric pressure and there is no possibility of a suction being applied to the paper which would tend to make it stick to the bottom felt.

The suction box in the top roll is primarily responsible for ensuring that the sheet follows the top felt and commences at about the centre of the nip. The suction area could extend into the ingoing side of the nip in which case some water from the paper would be drawn into the transfer felt; although this might reduce the moisture content of the paper slightly at mid-nip, this method of operation is not likely to yield an improvement because the transfer felt should be as dry as possible to obtain the best results in the next press nip.

The transfer felt and the paper must lap the top roll beyond the suction box area and, especially in the cramped situation of a stack press, they could possibly be arranged to leave the top roll at a point in relation to the sealing strip which encourages water in the holes to shoot inwards into the top roll. In this way, according to Dixon (1), the water can be collected easier than by trying to fit a tray in a very awkward position. The condition best suiting this method of operation (see 4B.3 3) will be achieved when the vacuum in the holes of the top roll is broken first on the outside by the felt leaving the top roll and immediately afterwards on the inside as the trailing side of the sealing strip is passed. The precise position where this takes place can only be found by experiment and for this it is generally necessary to be able to observe what is happening in a roll with an open-ended construction. The lead roll over which the transfer felt and paper passes must be adjustable within reasonable limits to effect the desired felt direction.

In practice, the use of a subsidiary air chamber using low vacuum, high velocity air is necessary to ensure that water is not thrown out. This chamber is situated adjacent to and on the trailing side of the main suction box, and is very effective though difficult to engineer in the space available. The alternative, of course, is to try to delay the throw-out of water in the usual way (possibly by using an extra wide trailing seal-strip or an air-bleed arrangement) until a point round the roll is reached where it is possible to construct a tray between the top roll and the felt which catches and retains water thrown out from the holes. In addition to this a nozzle can be built to project into the nip with a high-velocity low vacuum air connection to catch and draw up the spray.

The paper will always stick to the smoother surface it contacts in a press nip so that transfer is usually eased by selecting a denser and closer transfer felt and this fortunately approximates to the desirable characteristics of a second paper felt. The suction applied to the top roll box can then be reduced to a minimum which considerably lessens the water taken into that box.

The same general principles apply in whatever form the transfer press operates though it will be noted that where the paper is on the underside of the carrying felt, as it would be for example if coming straight from a suction pick-up roll, transfer is from the top felt to the bottom felt. In this case it would not generally be practicable to use the top roll suction box to extract water and normally the top roll would be plain and the bottom roll suction box would undertake the dual function of aiding the water removal and effecting the transfer.

331

The double-felted transfer nip has now lost its popularity in favour of transfer from a pick-up felt direct to a granite plain roll. With this arrangement it is simpler both to feed up the sheet and avoid the complications of water throw-out which have just been described. Except for very lightweight papers the open draw necessary from the plain roll to a second press felt is not disadvantageous and avoidance of two felts in the transfer nip enhances water removal. The pick-up roll may have two separate suction compartments, one to effect the pick-up and the other to aid water removal in the second nip where the web transfers to the plain roll, or in some modern designs a single wide suction box accomplishes both functions. The latter arrangement ensures that the felt and paper adhere to the suction roll between the point of pick-up to transfer, but is perhaps not so flexible for adjusting water throw-out at the transfer nip in cases where this is critical. A further advantage in transfer to a plain roll is that broke disposal is simpler. The full width of web can be doctored into an extension of the hog-pit underneath the plain roll, whereas with transfer to a second felt it is necessary to make provision to dispose of the full web at the second press, which with faster machines is often inconvenient.

4B.4 SUCTION ROLL CONDITIONS

The preceding section has dealt in detail with the position of the suction box in a suction press roll and with the critical setting of the trailing sealing strip. These factors have been seen to play an important role in controlling conditions particularly in the outgoing side of the press nip. In the present section attention is directed towards examining the influence of the vacuum exerted in the suction box and in addition some reference will be made to the air-bleed principle. A greater or higher vacuum is understood to mean a lower absolute pressure, i.e. a higher amount of vacuum relative to atmospheric pressure.

4B.4 1 Factors affecting the suction box vacuum

It is common practice with a suction press to use a constant-volume vacuum pump, usually of the liquid-ring type. A vacuum breaker or limiting device of some other kind may be used to prevent the vacuum rising beyond a point which would cause trouble on the press; as the vacuum in the press suction box increases, added friction at the box seals usually has a noticeable effect on the power demand which, if allowed to carry too far, would lead eventually to overload of the press drive motor or belt drive. This is particularly important at start-up when the press load will initially be very heavy until the bearings and other equipment approach equilibrium temperature.

During normal operation the vacuum attained in the suction box becomes a useful indication of performance and condition of the press. The greater the volume of air drawn by the pump the lower will be the vacuum achieved; the running vacuum thus gives a measure of closeness of the seal in the press roll and can be expected to be higher when the paper is thicker or less porous and when a felt is getting older and so is less porous. However,

evacuation of air from the holes in the press shell can also be shown to have an important bearing on the normal running vacuum because the holes entering the influence of the suction box carry air which is initially at atmospheric pressure; the greater the vacuum in the box the higher will be the effecitve volume of air (reckoned at normal atmospheric pressure and temperature) which the pump will have to cope with to reduce the air pressure in the press holes to that in the box. As the holes in a press roll become plugged they carry a lower volume of air and thus, with other conditions the same, a greater vacuum would then be expected.
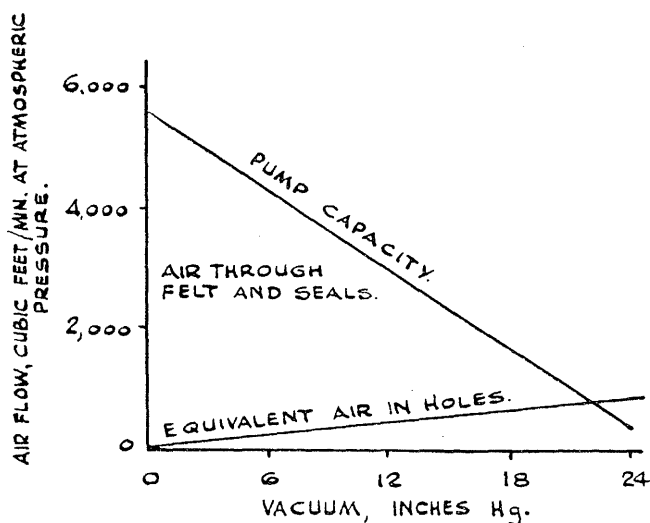
Fig. 4.9. Characteristics of a vacuum pump compared with equivalent volume of air required to evacuate holes in press shell (after Wahlström)

There are two reinforcing considerations governing the vacuum achieved. A higher vacuum is associated at the pump with a lower volume of air but it also means that more of the air that is drawn through the pump will simply have come from evacuation of the holes and less will have been drawn through the sheet (or equivalently through a poor seal). Likewise a lower vacuum is associated at the pump with a greater volume of air but also less of the air drawn through the pump comes from evacuation of the holes and more must have been drawn through the sheet (or through a poor seal). It appears then that the vacuum is a sensitive indication of press condition because quite small changes in sealing conditions resulting in alteration in the volume of air drawn through the paper and felt will give correspondingly large changes in vacuum. These points are illustrated in Fig. 4.9 which shows the characteristics of a vacuum pump as given in reference 21.

4B.4 2 Effect of varying the suction box vacuum

These comments do not resolve the question of which is the more desirable in order to extract water from the sheet, a high vacuum or a high flow of air through the sheet? It is clearly not possible to have both so it is interesting to turn to reports of experimental work to see what indications there are as to which is preferable.

There are only two reasonably comprehensive reports of experimental work in the literature in which the effect of deliberately altering the suction box vacuum with other conditions constant has been investigated. Jordansson (10) on the experimental machine at Stockholm decreased vacuum from 14 in. Hg to 4 in. Hg and noted only a small decrease in dryness of the sheet leaving the press. The quantity of water collected through the pump depended to a much greater extent on the machine speed and above a certain speed (which depended on other operating conditions) no water at all was extracted by the pump, leaving a greater quantity to be ejected from the holes further round the roll.

Wahlström (21), in his work, varied the vacuum on a second press between 19 in. and 9 in. Hg and found no significant change in paper moisture except at very low nip pressures when decreasing the vacuum increased the moisture content of the paper.

Dixon (1) and Sulatycki (20) confirm that little water is extracted in the suction pump so the concensus of opinion is that at reasonably high speeds and nip pressures the vacuum in the suction box is not critical. It is probable that to a great extent the suction in the press holes is important only insofar as it helps to direct air flow in the critical stage when the felt leaves the roll and the suction box is unsealed.

4B.4 3 The air-bleed arrangement

If the actual vacuum in a suction box is not of great importance can it be said that increasing air flow by allowing air to leak directly through the felt and thereby running at a lower vacuum improves the performance of a press? This is the principle of the air-bleed as described by Molsberry (6) in which an extra-wide suction box allows air to be drawn through the felt on either side of the nip; the paper follows close to the top roll and does not provide any sealing effect entering or leaving the nip.

There are some practical difficulties to this arrangement, especially on entering the nip, where Pollard (15) has reported trouble with blowing and blistering which could only be overcome by wrapping the sheet tightly round the top roll. In addition when leaving the nip, as the felt is still under vacuum when the paper separates from it, there is a natural tendency for the paper to follow the felt which can be very troublesome when threading through.

These difficulties apart, the evidence of whether the flow of air through the felt has a significant effect on press performance is not sufficient to draw definite conclusions. Jordansson (10) simulated an air-bleed arrangement on the outgoing side of the nip and found a slight increase in dryness but only at slower speeds where water was still being drawn through the

suction pump. Wahlström (21) experimented with moving the position of the suction box in a second press and with increasing air flow at a constant vacuum by allowing air to be drawn through the felt in the outgoing side of the nip. Apart from encountering similar practical difficulties to those reported by Pollard (the paper tended to stick to the felt particularly at the edges when the felt was dirty) no particular change in sheet dryness was noted.

Wahlström concludes that the position of the trailing sealing strip of the vacuum box is more important with regard to keeping the felt clean and dry and the small increase in dryness of the felt achieved with the air-bleed can have had only a marginal effect on the efficiency. It may be noted particularly that the influence of reducing the felt moisture content by air-bleed in the ingoing side of the nip would be expected to be greater for a second than a first press where hydraulic pressure components within the felt have less influence on the efficiency of water removal. However, both these investigations applied only to bleeding air through the felt on the outgoing side of the nip; it is possible that an air-bleed arrangement for the ingoing side of the nip would have more effect if the practical difficulties can be overcome satisfactorily.

The weight of evidence indicates that within wide limits neither the vacuum nor the air flow has much influence on press performance. It would therefore appear prudent to keep the vacuum fairly low, thereby minimizing frictional losses and power requirements. The use of a Sulzer centrifugal exhauster and blower in place of a normal type of suction pump would seem to commend itself as a means of satisfying this condition economically and it may be noted that a recent report (23) has commented on the lower power consumption and economy of hot air usage in the dryer section which accrues from using this type of equipment.

4B.5 MACHINE SPEED AND DRAW CONTROL

The effect of machine speed on press performance has already been mentioned in various contexts. Increasing speed hinders the efficiency of water removal in two direct ways. First, and most important, the decreased time of passage through the nip means that expressed water has to travel faster in relation to the felt to escape out of the nip or into suction-press holes within the ingoing side of the nip. To overcome this it is important to reduce the resistance to flow in the felt so a more open felt is needed. Second, the greater quantity of water handled in unit time means that the felt has less time to absorb water from the paper under the influence of the hydraulic pressure difference operating across the surface of contact. To overcome this a greater specific pressure and hence a greater load on the press is required. Both these effects are a result of the decreased time in the nip. But increasing speed has another effect on performance of a press which has been termed the 'wedge effect'. The hydraulic pressure of water in the felt rises with increased speed due to the greater velocity backwards through the felt which is needed to permit removal; for a constant applied load on the press, this greater hydraulic pressure has the dynamic effect of

wedging the rolls apart and allowing a greater percentage of water in the felt to pass through the nip. The result of this increased separation of press rolls in practical terms is still disputed.

This direct influence of machine speed has been investigated by Jordansson (10) and Fig. 4.10 reproduces some of the curves he obtained for dryness of the web leaving the press under different press loads. All other conditions were constant except that above 300 metres/min. there was a steady increase in the moisture content of the web entering the press which would contribute to the decreased dryness after the press.
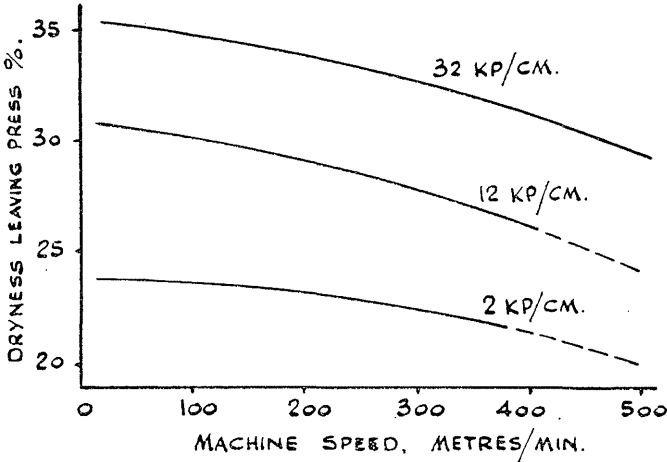
Fig. 4.10. Influence of machine speed on suction press performance at different press loads (after Jordansson)

Machine speed has other effects on press operation. Felts are run in faster but because of the greater quantity of water they handle the detrimental effects of plugging will appear earlier. Increasing speed will have an effect on the throw-out of water from a suction press shell and it was mentioned in the previous section that a speed is reached when little or no water is taken out through the vacuum pump. The conditions governing the direction and force of the throw-out of water in relation to the relative position of the end of the trailing sealing strip and the point where the felt leaves the roll are also influenced by the time element; a large change in machine speed might require an alteration in the direction of the felt run leaving the nip of a suction press if rewetting of the felt is to be avoided.

4B.5 1 Draw from press rolls

It is not proposed here to discuss the question of draw control at the presses in any detail as the subject has already been considered with regard to an open draw from the couch where the influence of the various factors is more pronounced and readily observed. Setting the speed difference

between the presses and between the last press and the drying section to produce a suitable draw tension is nonetheless an important part of the machineman's activities, even though the situation becomes less critical as the sheet gets drier. In one sense the conditions at press draws are simpler than at the couch, as there is no question of adhesion varying with the reabsorption of water from the wire. But the same general conclusions apply for press draws as the couch, that in practice they are almost always run too tight; once the machine is settled down, in most cases draws should be slackened back to a point where the angle of take-off is close to 90 deg.

The draws at the presses in most cases involve a speed differential of about 1 to 2 per cent. and on many machines, especially fast ones, it would be a useful guide to the machineman if he had an accurate indication of this. Such an indication would be partly useful in pre-setting the draw at start-up, but the main advantage would be to give a measure of the adhesive force between the sheet and the roll and prevent it becoming excessive. This can be done to some extent by observing belt positions, or some mechanical or electrical setting, but all of these are influenced by other factors.

Recent experimental work on handsheets by Radvan and Karpati (31) has shown that adhesion increases with speed and beating (of sulphite pulp), while other variables such as fibre composition, temperature, ingoing moisture content, and roughness of the roll all have some effect on adhesion. Varying the pH of the water in which the handsheets were made between 7·0 and 4·5 surprisingly showed no effect on the adhesion measurement. On many machines the pH of the backwater is treated as a sensitive value to watch and if allowed to rise too high from an acid condition the press doctor on the top roll will soon exhibit a growing collection of fibre stripped from the sheet.

4B.6 MOISTURE CONTENT OF PAPER ENTERING PRESS

Two investigators, Jordansson (10) and Wahlström (21), have produced some figures on the effect on press efficiency of differences in the moisture content of the paper entering the press. It would be expected from the theory that variations in ingoing moisture content would have a more pronounced effect in the second press than the first because the point within the nip where saturation of the paper is reached is more critical in the second press. Wahlström's work, which covered both a first and second press, confirmed this; in Fig. 4.11 it can be seen that the slope of the graph relating ingoing to outgoing moisture is much steeper for the second press.

It also appears from both sets of observations that the action of the press has a damping effect on moisture variations in the sheet; an alteration of couch moisture content from 80 per cent. to 88 per cent. in Jordansson's experiment led to only a 0·5 per cent. increase in the moisture content leaving the press. In Wahlström's graphs a reduction in the couch moisture content from 4·0 to 3·5 lb. water per lb. paper (12·5 per cent. decrease) led to a change from 2·22 to 2·08 lb. water per lb. paper after the first press

(a 6·3 per cent. decrease). Similarly this led in turn to a change from 1·97 to 1·91 lb. water per lb. paper after the second press, which represents only a 3 per cent. decrease. Thus a 12·5 per cent. change at the couch produced on average only a 3 per cent. change after the presses.
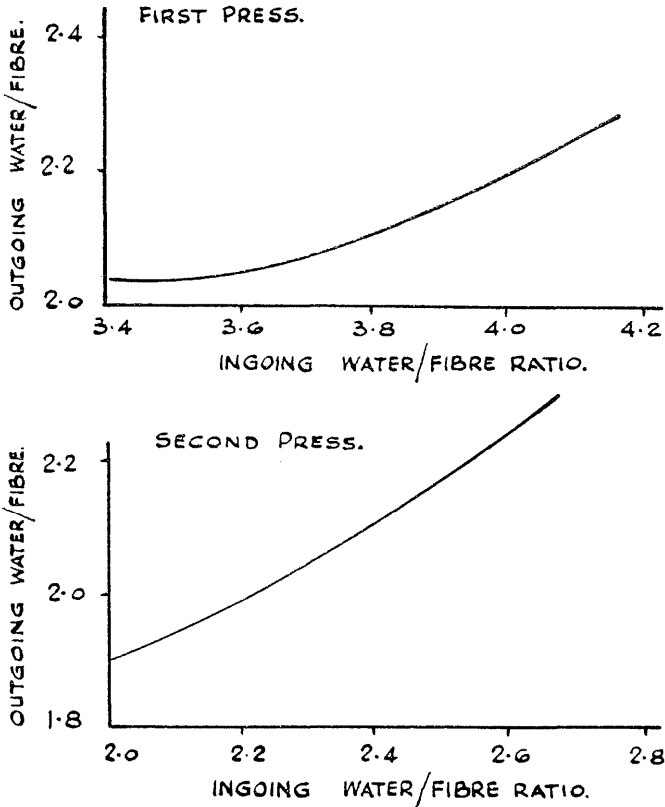
Fig. 4.11. Effect of changes in ingoing moisture content on outgoing at a first and second press (after Wahlström)

These results are important because they indicate that the actual quantity of water removed by a press is very dependent on the moisture content of the paper entering it. Further, the shapes of the curves in Fig. 4.11 show that the more water there is to remove the more proportionally the press will take out. It is not, therefore, so critical that the paper should leave the couch as dry as possible.

Certainly it appears that the drier the paper entering the press section the drier it will be entering the drying section, other things being equal, but the shape of the curves in Fig. 4.11 shows this to be very much a case

of diminishing returns. It would hardly be worth while prejudicing forma-
tion by running insufficient water on the wire, or shortening wire life by
having excessive vacuum on the suction boxes, if the motive were only to
achieve a low moisture content leaving the couch. On the other hand if the
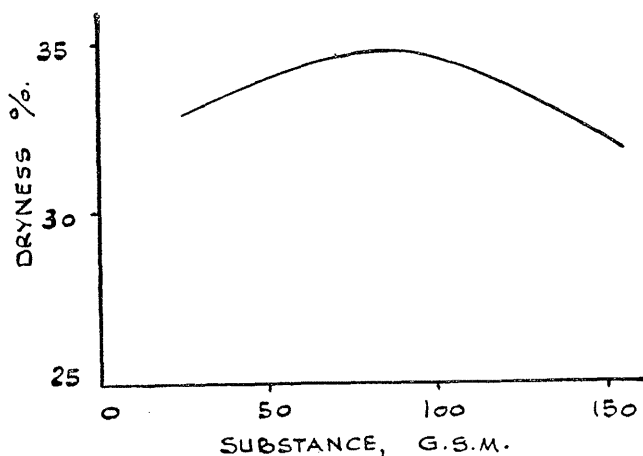
Fig. 4.12. Variation in moisture content of sheet leaving press with sheet substance
(after Jordansson)

sheet is allowed to become much damper entering the press section it is
evident that it will begin eventually to have an increasingly important effect
on the moisture content leaving the press section.

4B.7 PAPER PROPERTIES

The influence of paper properties on press performance has already been
mentioned in two contexts. Variations in the degree of beating of the stock
influence the adhesion of paper to the press roll. Also to certain extent
the thickness of the sheet has an effect on the moisture content leaving a
press nip.

Jordansson (10) found that with other conditions constant there existed
a certain sheet substance at which the dryness leaving the press was highest.
For lower substances the reabsorption effect would be expected, following
the experimental work of Sweet (26), to cause the dryness to decrease with
increasing sheet substance. Presumably also, increasing the substance
beyond a certain point so increases the quantity of water entering the nip
that there is increasing resistance to the greater flow within the felt and this
has the effect of reducing the final dryness of the sheet. Fig. 4.12 reproduces
the graph obtained by Jordansson, showing the effect of substance on the
moisture content of the sheet leaving the press. The moisture content
leaving the couch also varied with the sheet substance, but not sufficiently
to account for the shape of the curve as shown.

Both Jordansson and Wahlström (21) state that increased freeness gives an increase of dryness of the sheet leaving the press and this is attributed to the effect of the fines content and fibrillation on the size of capillaries in the paper. A greater degree of beating and the presence of more fines produce a smaller average capillary size; this will both retard the passage of water into the felt under the hydraulic pressure gradient within the ingoing side of the nip and increase reabsorption from the felt within the outgoing side of the nip, both of which will reduce the water removal. A graph given by Jordansson is shown in Fig. 4.13 and illustrates the
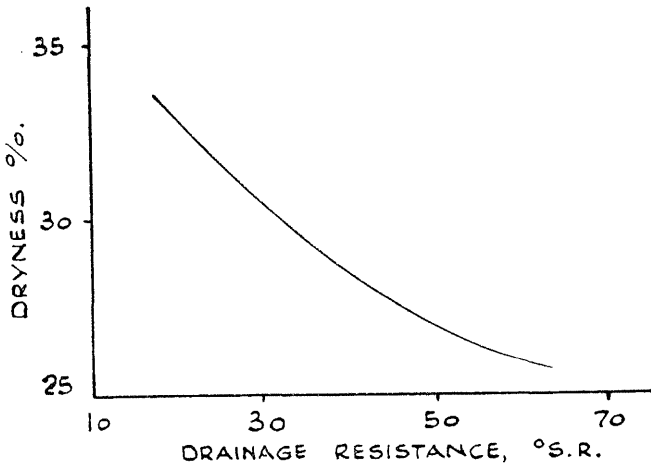
Fig. 4.13. Variation in moisture content leaving press with drainage resistance (after Jordansson)

effect of beating on the moisture content of the sheet leaving the press. (There was in this case hardly any variation in moisture of the paper leaving the couch.) It was also noted that the vacuum in the suction press increased from 11 in. to 14 in. Hg over the range of 19 deg. to 66 deg. S.R., which further illustrated the effect of closing up the sheet.

A similar point has been made by Wrist (47), who considers that next to loading on the press the furnish has the most influence on water removal. A sheet made from a pulp high in fines and fibre debris was found relatively difficult to dewater by pressing in an experimental set-up, but removing the fines fraction considerably increased the water removed under similar conditions and also lessened the tendency to crush.

4B.8 TEMPERATURE

By lowing the viscosity of water and hence reducing the flow resistance, an increase in temperature would be expected to assist water removal at the presses in the same way that it promotes drainage on the wire. There are

one or two reports evaluating the effect of temperature change produced by applying heat at the press in various ways and these vary somewhat in their estimates.

Wahlström (21) carefully tabulated the effect of temperature change during start-up periods and calculated that a 10 deg. F. increase in temperature of stock in the breastbox reduced the water/fibre ratio of the paper by 0·15, 0·08 and 0·04 lb. water/lb. paper at the couch, first press and second press respectively. The effect of temperature rise in the breast box is considerably reduced by the time the presses have been reached so that these figures in fact refer to a lower effective temperature rise at the presses; an actual rise of 10 deg. F. in temperature at the presses was calculated to yield a reduction of 0·12 lb. water/lb. paper leaving the second press. This reduction represented approximately 6 per cent. of the water in the paper entering the drying section and would thus give a very considerable decrease in steam consumption.

Increasing temperature at the presses has been recognized for some time as an effective means of improving press performance and there are several publications and patents which deal with this. Heating the stock itself in the breast box or pit, or by steam directly on the wire, could hardly be justified solely for the improvement in dewatering it would produce at the presses. These methods are adopted on many machines where a quicker drainage on the wire is necessary to increase production, but the improvement in press efficiency would then be regarded as a marginal benefit.

Other methods depend on applying heat directly at the presses. The use of infra-red radiation produced from oil, electricity or propane gas and directed on the paper has been reported and various claims have been made that such applications are economically worthwhile (3, 17). It is important to have the predominant wave-length of the radiation chosen to suit the particular application since the useful wave-length band for heating is restricted and depends on the thickness of water film.

Preheating the felt or paper with steam or hot-air is another approach that has received attention while another technique involves impinging open flames from gas burners directly onto the sheet. Yet another system is to pass a high voltage alternating current through the felt and paper either in the press itself, when a special metal wire can form one of the conductors, or separate from the press (12, 16, 29). The possible hazards involved and the economic validity of each of these methods require very careful consideration and to provide an accurate assessment it would be necessary to obtain figures relating reduction in steam consumption with increased dryness of the paper entering the drying section.

It is reasonable to assert that the most promising technique both practically and financially would very likely involve heating of the felt in the second press. Heating of the felt itself is important because it carries round by far the greater quantity of water entering the press nip and it is through the felt that water from the paper is expressed; also of the two presses improvement at the second press is more likely to be useful because it handles much lower quantities of water and the effect of a reduction in moisture content of the paper carries straight to the drying section.

4B.9 EQUIPMENT

It is not proposed in this section to enter into any detail regarding the relative efficiency of various types of presses even if enough comparative information were available to be worth quoting. The general characteristics of the basic types of press are well known and the present trend in design seems to be towards a compromise between the ease of maintenance and layout of an ordinary pick-up and suction press followed by one of several types of second press compared to the lower overall power requirement and use of machine space of the stack press.

4B.9 1 Press rolls

In the discussion on the influence of nip width it was mentioned that, especially where load is limited, it is important to keep the width of the nip narrow. One way of achieving this is to use harder rubber covers and comparative results on an experimental plain press with rubber covers of different hardness have confirmed that this has a very important influence on water removal efficiency (20). There have also been other reports of the beneficial results obtained on machines by using harder roll covers; in one case increasing hardness from 45 deg. to 17 deg. P & J decreased the moisture content by as high as 4 per cent. (21). In the same way, smaller diameter rolls and thinner rubber covers will reduce the nip width and hence can be expected also to have a similar effect in improving the efficiency of the press.

The main disadvantage to running with very hard rubber covers, or even no covers at all, is that small discrepancies in the camber shape become relatively more troublesome. Any small bruise in the roll causes a wet spot in the paper and produces a blemish at the calenders. Opposed to this softer rolls, apart from reducing the press dewatering efficiency, are more difficult to grind and the rubber distorts more within the nip. This distortion could, if the roll were very soft, be sufficient to reduce the diameter of the holes in a suction press to a point where they ceased to be effective. But apart from this the rubber bulges on either side of the nip, particularly on the ingoing side because of the effect of the bottom roll drive, and the relative motion of the rolls in this region will subject the felt to greater wear (20).

The holes in a suction press should be as small as possible. Water collected in the holes of a typical press occupies only a small fraction of the volume of the hole so there is no fear of the hole becoming waterlogged. The smaller the diameter of the holes, the more holes can be put in the shell and the smaller can be made the distance between holes round the circumference of the roll. The advantage of this has already been stressed and would be especially valuable in the first press. Further, the volume of a hole is proportional to the square of the diameter, so a greater number of smaller holes will have a proportionately lower volume of air to evacuate and this will reduce the demand on the vacuum pump.

Whether the practical limits of reducing hole diameter have not already been reached in an endeavour to minimize the possibility of shadow mark-

ing is difficult to say. In mills which experience trouble with the holes getting made up it would probably not be feasible to reduce their diameter further. Also small lateral distortions of the rubber cover in relation to the metal surface of the main shell of the roll onto which it is bonded would be more troublesome in throwing the holes in the rubber and shell out of alignment.

Finally with regard to suction roll holes it may be mentioned that it is preferable to pitch the holes slightly across the length of the roll. This evens out the area of holes coming under the influence of the suction box at any one time as the roll moves across the box, and reduces the chance of oscillation of the air flow and vacuum.

An investigation has been made (9) in an attempt to reduce adhesion of the paper to the top roll which becomes more troublesome at faster speeds; it appears that the adhesive force depends partially on chemical characteristics and partly on the micro-geometrical nature of the roll surface. Ground but unpolished granite has lower adhesion than polished granite, but some hard synthetic rubbers give the best results. These general findings are in broad agreement with recent experimental work by Radvan and Karpati (31).

4B.9 2 Ancillary equipment

It is becoming more common now to see the doctors on top press rolls air-loaded and oscillating slightly across the machine. These features have a definite advantage in minimizing wear in localized positions across the roll and reduce considerably the possibility of trouble eventually occurring with fibre lumps passing under the doctor and into the press nip. Air-loaded suction box seals are also proving beneficial for the flexibility they offer.

On faster machines the simple tray behind the doctor becomes inadequate to collect the sheet as it runs up the press and is being superseded by a belt conveyor which removes the broke from the machine as it piles up behind the doctor. Alternatively a special rotating screw pulper to which water is added can be used to break up the sheet and dilute it for pumping to the broke chest. It is possible to have both these systems started manually by the operator although, as they would usually be installed on faster machines, automatic operation is desirable to avoid jams. In this case the mechanism could be actuated by signals from photo-electric or ultrasonic break indicators but an alternative is to use a light aluminium feeler attached to a microswitch which senses when the sheet begins to build up on the doctor and then sets the conveyor or pulper into motion. Modern designs for the first press overcome the problem of broke disposal by arranging for the web to be doctored off straight into an extension of the hog-pit.

On some presses water throw-out from the holes in the suction roll can be delayed sufficiently to cause wetting of the felt at the ingoing side of the nip and this would be expected to have an adverse effect on the water removal efficiency of a press. This was confirmed by Wahlström (21), who

devised a rubber doctor suitable for contacting the bottom suction roll of a second press. The doctor was shaped to deflect water thrown against it away from the roll and proved to yield a significant improvement in performance. A subsequent modification of the original design has been described by Delisle *et al.* (37).

It is usual to have a water shower inside a suction roll, and stretching across the full length of the roll, the purpose of which is to lubricate the inside of the shell and minimize friction with the suction box seals. Such a shower is particularly useful during start-up periods when it is important to prevent the press using excessive power, but later on it is rarely necessary to use a high pressure on the shower and may even be possible to run without it at all. If the press uses no more power nor sounds any different with a reduced shower pressure it is preferable to retain the lower pressure in order to avoid the possibility that the splashing of water into the suction roll holes may adversely affect water removal in the press nip (the author has known even a clean, well-adjusted spray to increase the average moisture leaving a press by 2 per cent.). Further, in mills using hard water it is easy for uneven wear of the suction box seals to occur and uneven deposits in the holes across the roll to build up due to the shower producing a jet stronger in some places than in others. This localized plugging of press holes and wear of the seals is difficult to observe and correct and eventually produces uneven water removal causing both the paper and felt to run wetter over the area opposite the badly made up holes. Using as little water in the shower as possible helps to reduce these difficulties, but in some cases it may be advisable in addition to oscillate the shower. In some types of suction roll the spray is dispensed with in favour of water purges on either side of each sealing strip; this should, given a satisfactory design, be less liable to cause unevenness across the length of the roll.

RUNNING THE PRESS SECTION

4C.1 DAILY OPERATION

As for other parts of the paper machine the problem of keeping a control on the efficiency with which the press section operates is now considered from the standpoint first of day-to-day working, and second of longer-term running. In the latter case most attention will be given to the question of felt changing because this is the most important single maintenance problem. But other aspects of maintenance will be considered, in particular that of suction roll cleaning; also the purpose and value of having periodic tests of the press section efficiency will be discussed.

Another problem of press operation is that of keeping the press action as near as possible the same the full width across the machine. Some features of this problem are daily and some long-term, but it will be more convenient to treat this subject separately.

4C.1 1 Essential measurements

In the preceding chapter the influence of various factors on press performance was considered in detail and three measurements were frequently referred to: the load on the press, the vacuum in the suction box (for a suction press) and the power used by the press (for electrical drives). Each of these measurements can give a great deal of useful information on the state of the press and are vitally important.

An indication of the load on the press at both sides of the machine obtained by one or other of the methods discussed in **4B.1 3** is important primarily for accurate setting of the load applied. At start-up and when running-in a felt load has to be varied, perhaps over a fairly short interval, and this can be done more accurately and consistently when a proper indication is available. Although once a felt is run-in the tendency will be to adopt the same setting all the time, it may often be possible to put on a heavier load without crushing and an accurate load indicator is then useful for giving a figure to the higher load applied so that it may be tried again under similar conditions. When a press is run just under crushing load almost all the time, observation of how this load varies under different conditions should give a guide to the state of the felt and suction roll holes. Unless the press is faulty the load should always be exactly the same on both sides, which is why it is essential to measure and set the load applied at both the back and front of the machine. Deliberate application of uneven loading as a means of correcting a consistent moisture difference caused by a fault elsewhere on the machine is often resorted to, but should be avoided because it becomes over a period of time less and less effective and gradually ruins the press; this point will be fully dealt with in the discussion on cross-web variation in **4C.3**.

345

Both the vacuum in the box of a suction press roll and the power consumed by the press are of obvious importance for showing if something is radically wrong. But apart from that, careful observation and logging of the appropriate figures can give a useful indication of the state of the felt, suction box seals and holes in the press roll. If the vacuum is lower than usual it does not mean that the press will be working less efficiently but it may indicate that one of the seals is leaking or that the pump requires attention; greater speed will also reduce the vacuum because more air will be drawn from the press holes in a given time. More often the vacuum will progressively increase as the felt or press holes get made up and it should be realized that there is no benefit in letting it get too high.

The power consumption depends mainly on the frictional forces involved and these are increased by greater load on the press, greater speed and higher vacuum in the suction box. The draws would be expected to have a small influence on the power but probably the condition of the felt roll bearings and the tension in the felt are of more importance. After the sheet is threaded through at start-up the power consumption should gradually drop as the press warms to equilibrium running conditions; nevertheless, it is useful to have a warning device linked to the ammeter to ensure that the attention of the machineman is quickly drawn should the load become excessive.

4C.1 2 Useful measurements

There are two variables of press operation that, especially on faster machines, could beneficially be measured: the draws and the felt tension. The value of measuring the draws at the presses depends on the accuracy of the method; after the first press the draw may be under 1 per cent. of the machine speed and to obtain useful information an accuracy of probably at least 5 per cent. or so of this difference would be needed. This is a very exacting requirement but such accuracy must be attained if a draw measurement is to be of more use than the rough indications which are available anyway to the machineman.

The main value attached to measuring the draw is similar to measurement at the couch which has been discussed in detail in Part 3. Indirectly it enables a figure to be given to the tension in the sheet when the run of the paper web is in the usual operating position. When a draw is normally run fairly tight (in the sense that it is adjusted so that the paper peels off the top roll at a pretty acute angle) it is not easy by inspection to see that the tension is greater than usual, as it would be if adhesion of the paper to the press roll were higher. Measuring and keeping the draw to modest proportions, apart from helping to reduce the possibility of frequent breaks due to overstretching, will be of particular importance when the paper is required to have equal strength and moisture expansion properties in both directions (moisture expansivity is closely dependent on permitted shrinkage though this effect is of rather more significance in the drying section).

The tension of the felts in a press section is very frequently much too high. Apart from the probability of using more power to pull the felt round due to the increased friction on the felt roll bearings, the felt will be

strained by excessive tension and will almost certainly wear faster. High tension can be justified, for example, when the felt is too wide at the beginning of its life and tightening enables it to be brought to the necessary width for comfortable running. But normally the stretch roll should be slackened well back within the limit of the felt threatening to become uncontrollable.

Huyck Felt Co. have designed a simple device for measuring the tension of a felt when running. This instrument consists of two smoothly bevelled supports joined on a frame about one foot apart; in between is a weight which can fall below the level of the supports by a small amount which can be measured by a micrometer suitably attached to the frame of the instrument. In use the instrument is held by a handle attached to the frame and allowed to rest on the running felt; the weight pushes the felt down below the supports by an amount which depends on the tension of the felt and this can be determined from previous calibration of the micrometer reading.

Using this instrument it is possible to take periodic checks of felt tension and this may help to keep the tension down to a reasonable level. Alternatively it is not difficult to attach a strain gauge to the stretch roll mechanism to give a continuous measurement of the tension. Modern stretch mechanisms which are pneumatically and hydraulically loaded have the advantage of giving a direct indication of felt tension.

4C.1 3 Measuring moisture content leaving the presses

Each of the measurements discussed above provides essential or useful information to assist the operator in running the presses efficiently and help him recognize and diagnose the cause of unusual conditions. But he still has no direct assessment of how well the press is performing its primary function—to remove water.

Ideally a continuous record of the average moisture content of paper entering the drying section would be invaluable. The beta-ray gauge has been used for this purpose but there are several difficulties which, though they can be overcome in a research investigation, need careful thought if the instrument is to be useful for unsupervised daily operation. Two of these difficulties are worth mentioning. On most machines there is likely to be substantial variation in moisture content across the web and unrepresentative readings would be produced if, for instance, the head of the beta-ray gauge coincided in position with a damp streak in the paper. This could only be overcome satisfactorily with either a traversing mechanism or using more than one head and both of these methods are expensive. The other difficulty relates to the fact that the beta-ray gauge measures the total weight of the sheet, fibre plus moisture, so that variations in the dry weight of the sheet will affect the moisture content figure. The machine direction substance fluctuations may not be sufficiently great for this to give a serious error when averaged over a reasonable period of time, but cross-web variations would on all but the most stable machines add complications in ensuring a representative position. A beta-ray gauge reading from the reel-up subtracted from a press gauge in the same cross-web

position provides one solution to this problem; but it does not even then take account of variations in the moisture in the paper at the reel-up though this presents no particular difficulty when a moisture meter is used at the dry-end.

Despite these problems some continuous indication of the average and also in some cases the profile moisture content entering the cylinders is likely in the future to become standard equipment and at least one type of moisture meter has been developed which is claimed to have a high accuracy at this position. The advantages for the operator would be very important because he would be able to observe immediately the effect of making alterations to the press operating conditions. Adjustment of load on individual presses and the balancing of total load between the different presses would make a change to the moisture content of the sheet leaving the presses which could be assessed straight away, and this would encourage the operator to experiment with changing the load much more than is customarily done at present on most machines. Further, when alterations are made to the wire conditions, in particular to the volume of backwater circulating round the wire pit and mixing pump and to the vacuum on the suction boxes and couch, any change in the moisture content of the sheet at the couch which became transmitted to the drying section would be immediately shown up. Over longer periods changes in the average level of dryness of the paper leaving the press section would permit the felt condition and the usefulness of cleaning the felt in various ways to be assessed. Conditions in the drying section could also be watched more easily if the dryness level entering the section were compared with the steam flow.

4C.14 Measuring water extraction at the presses

It is possible to obtain information from the presses yielding most of the benefits mentioned in the preceding paragraph without attempting the difficult task of measuring the actual moisture content of the web. This can be done by obtaining a measure of the volume of water extracted by each press. In some respects treating each press individually has additional merits from the point of view of trouble-shooting and considering the relative ease and simplicity with which it is possible to measure water flow from presses it is surprising that this is not done on more machines.

In the case of a simple plain press, water collected in the trays is generally channelled to one side of the machine and led to a drain. It is not difficult to arrange the flow so that it passes over a suitably-sized weir or flume giving a direct visual measurement of the flow. By using a simple float and cable element or the back-pressure in an air bubble-tube system placed below the level of the weir, this can be elaborated without much cost to give a continuous record; the flow from two presses can be displayed simultaneously on a two-pen recorder.

The reliability of this measurement depends to a large extent on whether other flows of water to and from the press represent a significant part of the total flow; this particularly concerns water added to the felt in cleaning

348

and water removed by suction in the felt cleaner and the suction box prior to the press nip. If these flows amount to 10 per cent. or more of the main flow from the press tray, and especially in the case of water added in cleaning they may quite easily, then it would be preferable to ensure at least that the water added in felt cleaning is kept constant; this is likely to apply particularly to a second press where the main flow is smaller. This step is advisable anyway and can easily be accomplished by incorporating a small rotameter in the line to allow the flow to be set; alternatively, if the flow with a fixed entry valve position hardly ever varies, it may be sufficient to set the valve to a standard opening and have the flow checked and adjusted periodically by the laboratory staff. With a suction press, water extracted by the suction pump presents an added difficulty. However, it has already been mentioned that in most cases the suction pump appears to extract little water so that any variations in this flow may be regarded as negligible. A simple check can be made by temporarily shutting off priming and sealing water to the pump and measuring the remaining volume, which should then be the flow from the suction press box; provided this flow stabilizes before vacuum begins to alter as the pump is starved of water, the figure obtained would be reasonably accurate. If such a test proves the flow to be substantial it can be added to the main flow from the press tray for measurement. In this case it would be important to keep the pump sealing water constant in a similar way to the felt cleaning water. Finally, the water added in the suction roll spray would also need to be regulated as this usually represents an appreciable fraction of the total water removed in the tray.

Although the points detailed above may seem to involve many complications it must be remembered that the preliminary estimations of the various auxiliary flows require little preparation beyond arranging suitable tappings. If any were found to be variable there would be some advantage anyway in arranging for the flows to be regulated from the point of view of consistent press operation, apart from increasing the accuracy of the main press water flow measurement. The flow of water in a suction press internal spray has been known to give a great deal of trouble by causing cross-web moisture variations until someone discovered that a valve that used to be just cocked open had somehow gradually got turned fully open and was admitting a huge quantity of water to the spray.

To assess the potential value of measuring the flow from individual presses (assuming the necessary care with accuracy were taken in the manner described), it is worth considering the relative influence of various factors which will affect the flow. These may be divided broadly into variations in the paper itself in the form of moisture content entering the first press, substance, freeness, temperature, etc., and variations in the performance of the press itself due to load, suction box vacuum, felt condition, etc. Variations in the press water flow caused by the paper affect a first and second press in the same way, though to different extents, so that on a combined double pen recorder showing both flows the traces would follow roughly parallel. By contrast, variations due to the press itself (load, felt condition, cleaner operation, etc.) will show up as a

349

separate movement in the relevant trace and the effect of making altera-
tions can be readily observed. Further it should be very easy to see what
happens to the water removal of a second press when an alteration is made
to the first press, and hence to adjust the total load appropriately. In
day-to-day running the operator should be able to distinguish without much
difficulty between effects caused by the paper and those attributable to the
individual presses and this will assist him in no small measure to keep the
performance of the whole press section at a high level.

4C.2 MAINTENANCE OF THE PRESS

4C.2 1 Felt changing

The most frequent and important aspect of running a press that comes
under the heading of maintenance in its broadest sense is clothing renewal.
The life of a wet felt can vary from a few days on a fast machine to several
weeks. On most machines felts are generally taken off the press when it
becomes fairly obvious that their performance has deteriorated; the felt
may have worn severely in some place or more likely it may have become
so hard and plugged that the load has to be constantly relieved from the
press to prevent crushing while a noticeable increase in drying steam
pressure become necessary.

Policies with regard to felts vary considerably but as with other clothing
it is fairly safe to say that in a majority of mills the papermaker regards it
as one of his obligations to get as long a life as possible from the felt. He
may do this by stipulating careful washing, and in some cases possibly also
turning, of the felt at every opportunity when the machine is stopped, or
even require that the machine is stopped occasionally for that purpose alone.

Some form of record will be kept in which the various makes and types
of felts used on the press are listed, together with their cost and a means of
assessing their performance. The latter is usually in the form of the number
of days or weeks each felt lasted on the machine, the total distance run, or
the number of tons of paper it made and perhaps also the cost of the felt
per ton of paper. Such details together with general comments on the
running of the individual felts are, of course, an essential means of ensuring
that only suitable felts are used, and they help considerably to decide the
physical make-up and characteristics of the felt best suited to each particular
application.

The main weakness in this simple record system is that it emphasizes the
importance of getting felts which run satisfactorily, in the sense of being
dimensionally stable throughout their life, withstanding accidental damage,
not having weak places, etc., and which last longest, produce the most tons
or generally do best in whatever measure is taken of their performance.
These aspects are certainly important but there is no virtue in squeezing
the last ounce of life out of a felt at the expense of appreciable loss of
production in downtime. It is fairly easy to use most felt records to
determine in the first instance whether felts are being kept on too long, and
if so to estimate roughly how long felts of similar types may be kept on
the press before they become uneconomic.

Suppose, for the sake of example, that felts are normally used on a press from four to six weeks and that a straightforward record of the number of tons made each week by each felt is available. On machines which make a variety of different types of paper a simple total tonnage figure for each felt may not be considered representative of the work done by the felt but there is no reason why the individual figures for each making should not be weighted in some way to take account of this; this adds complications to the business of keeping convenient records, as would allowance for variable deckles and paper lost in the dryers but included in the tonnage figures, but these points must be decided on their merits and can probably in most cases be ignored without unduly affecting the accuracy of the figures.

During the first two weeks of the four to six week life, production can reasonably be regarded as uninfluenced in any way by the state of the felt (this assumes that the running-in period is not so long and difficult as to involve loss of production—only greater steam consumption). An average for these first two weeks taken over many felts will produce a figure which may be regarded as normal when the felt is satisfactory, and this may be compared with the average production in succeeding weeks of the felt's life. By a simple calculation it is easy to determine whether the average loss of production by retaining a felt for an extra week of life is uneconomic.

This procedure is, of course, a standard maximization problem and a person with a little mathematical sophistication would use the tonnage figures in a more rigorous manner to estimate how accurate the results are and to check that the conclusions do not give a false impression. Also, if a reasonably comprehensive machine log is kept, it is possible to check from recorded downtime caused by attention to a felt that this becomes greater later on in its life. But even a straightforward estimate along the lines first suggested is likely to show up some alarming facts and it is often surprising how little downtime on a machine immediately wipes out the small difference in average running cost of the felt achieved by gaining an extra week on the five, four, or less weeks already run.

In the author's experience it is well worth using this approach to determine whether, as is nearly always the case, felts are being left on the presses too long, and then to decide on a standard life for the felt in each position. This has the additional merit of permitting easier organization of clothing changes and provides the papermaker with a sensible economic basis for taking decisions to leave or remove a felt which is giving trouble. It will also, incidentally, be appreciated by the cost accountant working to standard cost figures and will allow clothing to be more easily purchased in a systematic manner (even, as an application of operational research techniques, with a frequency which reduces stocking costs to a minimum).

4C.2 2 Felt performance throughout its life

In the previous section optimization of felt life was considered from the point of view of preventing uneconomic loss in production as the felt ages. But experimental work has been quoted which shows that after a certain

length of time on the press the porosity of a felt is frequently reduced by materials plugging the interstices and then the efficiency of the press begins to drop. On fast newsprint machines this consideration may outweigh all others in deciding the life of a felt and as soon as steam pressure in the drying section begins to require raising the felt may be taken off. Though admittedly an extreme case, this illustrates that on most machines, particularly those using loadings and mechanical pulp which might cause rapid plugging of felts, this factor warrants investigation.

Most of the work involved in an inquiry into this aspect of felt life depends on obtaining figures which show up changes in the moisture content of the paper leaving the press. The complexity and variety of the experimental results obtained and analyzed for this purpose by Wahlström makes any investigation of this subject appear at first sight to be a formidable undertaking. Wahlström in fact emphasized that normal variations in ingoing and outgoing moisture content, disregarding extreme conditions at start-up or with a new felt, could be very high and made it impossible to characterize a press by means of occasional spot tests. This difficulty was well brought out by the completely negative results of the analysis of the 1958 questionnaire circulated by the B.P. & B.M.A. Technical Section which was designed to discover, amongst other things, how water removal and felt life are affected by felt type and general press conditions on different machines.

The main problem lies broadly in isolating changes in the water removal efficiency of the press due to the press itself, and in particular to the felt as it ages, from those caused by the paper, of which ingoing moisture content is the most important variable. By careful analysis of the moisture content of the paper before and after pressing Wahlström was able to isolate and allow for the more important variations caused by the paper itself and this enabled him to consider the influence of the press and in particular to discover how serious was the effect of the felt ageing on press efficiency. But this required press tests involving breaking the sheet for samples at fairly frequent intervals through the life of a felt. It is unlikely, as the author has in fact found, that analysis of spot test results, such as many mills take at intervals of a few weeks primarily for examining cross-web variations, would yield any useful information on this point.

An alternative approach, which has much to commend itself in a mill with restricted facilities for testing, is simply to observe the variations in water removed at the press and measured in the manner suggested in 4C.13. This preferably requires frequent makings at similar speeds of the same grade of paper, but over the life of a number of felts any decrease with age should become apparent. Similar observations of variation in steam usage in the drying section should enable an assessment to be made of the relative saving by keeping the felt on after a certain point in its life compared with the cost of using more steam for drying. The interaction of the presses on one another, in the sense that the less water is taken out at the first press, the more will be removed by the second, must of course be taken into account in a calculation of this sort and allowance must be made for variations under different loads, the other main press variable.

A further point worth mentioning is that felts which cause reduction in press efficiency by becoming plugged will show a considerable change in their physical properties before and after use. Unfortunately such changes occur anyway due to mechanical conditioning and the same difficulties in interpretation arise as were mentioned in connection with the measurement of porosity while the felt is still on the machine by using the Huyck porosimeter. It is not, therefore, likely that measurement of thickness, weight, density, tensile strength, chemical composition and other properties can help much to indicate whether the felt is being left on too long, though they may be useful in connection with the analysis of cross-web variation and for long-term checking and comparison of the performance of different types of felt. As such, these comprehensive tests on used felts would be undertaken at intervals on typical samples.

Another advantage to be gained by making an investigation of this nature is that it will give an idea whether or not the existing method of felt cleaning is adequate. If it appears that a felt should be removed from the press because it is badly plugged, yet otherwise it is in sound condition, then some new form of cleaning on or off the machine is obviously indicated. If figures for the increased steam costs due to plugging are available it will allow a sensible economic evaluation of alternative cleaning methods to be made.

Finally no papermaker will be content to determine a satisfactory type of felt and standardize its life, and then regard the job as complete. Felt manufacturers are constantly introducing new varieties of felt by altering the material, weave, and finishing processes and it is encumbent on the papermaker to recognize their efforts in this direction by giving a new type of felt a fair trial. In fact, of course, if reliance is placed purely on subjective comments received from the machine crews, then the papermaker deserves to lose the opportunity of improving his presses. It is certainly important to know that the felt runs satisfactorily, can be controlled on the press, and does not mark the paper, but how well it performs its primary function of removing water can only be answered satisfactorily by careful measurement. Here, again, appears one of the advantages of having to hand records of the average water removal by felts already in use so that an immediate comparison is possible.

4C.2 3 Other maintenance

Apart from the felt there is little on a plain press in the way of long-term maintenance that can be regarded as directly the obligation of the papermakers, as opposed to the engineering and instrument staff. The question of cambering of rolls is dealt with separately.

On a suction press it is necessary to clean out the holes at intervals. This should preferably be done on a routine basis for the same reasons that apply to felt changing, and observation of water removed by the press should, in this case also, help to lay down the frequency with which cleaning is needed. It is likely that the holes can get quite small in diameter without unduly affecting water removal and generally trouble will eventually

begin to appear at one point of the roll, rather than over the whole roll at once, causing cross-web variations.

Formerly the usual method adopted for clearing the holes was to punch or drill out the deposits from each hole individually, but most mills nowadays find that it is perfectly satisfactory to use strong alkaline or acid solutions specially formulated for this purpose by chemical manufacturers. These are best used at the moderate temperatures recommended and can easily be applied to press sections from a special tank equipped with a heater and pump, which circulates the chemical into the press roll and back through a suitably adapted collecting tray, while the roll itself is slowly revolved. This form of periodic cleaning can be assisted by the use of high-pressure water cleaning units which traverse slowly across the roll. In hard-water areas, where deposits can be very hard to punch out, loosening the adhesion of deposited solids by this means and then chemical cleaning, though it may require doing at more frequent intervals than punching, is then very much cheaper.

The suction boxes, seals, deckles, and sprays inside press rolls will require periodic inspection and cleaning and are conveniently examined all at the same time. The sprays whenever practicable should be tested off the machine where they can be observed and, if of the fan-tail type which are the best for this purpose, the distance should be checked to prevent overlapping of the jets in the press roll. If this is avoided deposits from the water are less likely to cause build-up in press holes at one place across the roll in preference to another. The load in use and oscillating mechanism for doctors require frequent examination, and the condition and angle of the blades to the roll surface also should be regularly checked. Records of the doctor changes giving details of the type used, condition when removed, life, etc., are of obvious use if a systematic check is to be kept.

4C.2 4 Long-term records

It has already been emphasized that any equipment on the paper machine should be made the subject of thorough checks at intervals and this applies especially to the presses. Press testing involving breaking down the sheet for samples to test for moisture content across the machine is often adopted on a routine basis for the purpose of controlling and spotting cross-web variations; this will be considered in 4C.3 4 but is, in the author's opinion, of limited practical value. It is, though, important to obtain this type of data periodically, when one of the major grades of paper is being run on the machine, for the purpose of long-term records of performance. The occasions when this is done are preferably chosen to avoid very new or old felts which may confuse interpretation of the results.

A thorough press test that is well organized need not require the sheet to be down for longer than five minutes. During this time several samples are taken at fixed positions across the sheet from all the relevant points of the press section, placed in suitable air-tight containers, and then tested for moisture content and the results expressed in the form of water/fibre ratios. Calculations from this data of water being removed from the sheet

in each nip should tally to within 10 per cent. or less with the quantities of water as measured leaving each press in the tray (sprays, felt cleaning water, etc., can be temporarily shut off to facilitate obtaining a quick and simple measurement). Other measurements that may be useful apart from the obvious ones of press load, power consumption and suction box vacuum are temperature of the paper, air flow to the suction pump, and draw.

4C.3 CROSS-WEB VARIATIONS

The problem of variation across the sheet in the press section is essentially one of keeping the moisture content profile as even as possible. If the moisture content were even across the sheet leaving the press section then the presses would have done a good job. Unfortunately this is rarely the case and the machine crews spend a great deal of their time trying to achieve this ideal. The main difficulty is, of course, that in the normal course of events the operator can only check the finished reel for evenness across the sheet so that the cause of any variation may be anywhere down the machine and location of it often represents the hardest task.

Cross-web variations attributable directly to the presses may be divided into three groups: those due to inaccurate cambering of the rolls, those due to differences in the felt dewatering characteristics, and those due to other isolated faults such as spasmodic plugging of press holes or uneven cleaning shower pressure. Transient fluctuations in moisture content across the web coming from the couch will be damped out in an efficient press section but permanent differences will gradually begin to have an adverse effect on press performance so that even an initially perfect press will eventually be thrown out of balance. In addition, each of these individual causes of unevenness reacts with the others and further complications arise. These problems have received a great deal of study recently, notably by Chinn (18), Sulatycki (20), Wahlström (21), Grant (24), and Delisle et al. (37) and the following sections draw heavily on their findings.

4C.3 1 Camber of the rolls

The subject of cambering rolls to ensure even pressure in the nip all the way across the roll is very complicated and it is intended here only to bring out the main points. There are three main aspects to the problem as it affects press rolls: to decide the magnitude of the camber required, the shape of the camber curve, and the distribution of camber between the two rolls forming the nip.

The magnitude of camber can be calculated with a fair degree of accuracy once the total load on the roll and certain physical characteristics of the roll itself are known. Apart from standard dimensions and weight the important physical constants which are needed are the Young's modulus of the roll and the point of balance in the journal bearings. Both these values can only be obtained approximately and the accuracy of the calculation is further affected by the fact that the rolls are always of different composition, in hardness if not in material, through their body. Further, since the camber depends on the total load on the roll it can be suited only to one running condition; if more load is applied to the press the nip pressure

will be greater at the edges of the roll, if less load the pressure will be greater in the centre.

Because of these difficulties it is usual to find the best camber by experience, although calculation can be a very useful guide if a new or different set of rolls are put into use. Any error in the camber will show up greatest when the roll is first put on the press; as the roll is run-in the places where pressure is hardest gradually wear more than the other places and the initial errors are evened out. There are one or two methods of assessing whether the camber is correct for normal operating pressure, but they are very approximate and with one exception can only be utilized in static conditions; most frequently used are the embossed foil or carbon impression techniques which depend on measurement of the width of a fairly ill-defined band so that only relatively gross errors of camber can be determined with any accuracy. A different technique has been developed by Sussman and Grimwood (44) which permits a dynamic check of nip conditions to be taken; in this method full-width strips of a suitably embossed aluminium foil are fed through the press while it is moving as fast as is practicable, and variations in the resultant thickness of the foil can, with calibration, be used to assess differences in nip pressure. However, all these methods are primarily of value to check that loading of a press is even on both sides and to avoid any excessive error in a new roll.

The best method of controlling the camber is, in the author's opinion, to determine the amount of wear across the roll periodically through its life and use that as a basis for fixing the camber for the next grinding. By this means the magnitude of the camber and also the camber curve giving the best compromise under average conditions can be found. The success of this approach depends, however, on there being no other persistent variations across the machine and this is usually where the difficulty arises. If the roll has, for instance, been loaded heavier on one side than the other or has gradually plugged in one place, then the wear curve will give a false impression. For this reason it is important to check the camber at intervals when the roll is still on the machine and determine from these figures an average wear curve. In theory once this has been done a few times it should become possible to lay down a definite camber figure, but in practice conditions are constantly changing on the machine (in particular, normal operating loads may be altered) and the procedure has to be continually repeated. Rolls should always be ground shortly before being put on the press to avoid the appearance of flats in storage.

On the machine, wear of the roll is influenced by many factors and the better the treatment of the roll the longer it may be run without reaching a point where grinding becomes necessary. If the drying is different on one side of the machine compared with the other and the machine crews habitually correct this by weighting the press roll heavier on the damper side, then the roll will wear more and more on that side until the load has gradually become almost even again across the roll; hence a greater and greater load difference will be needed as time goes on until the press becomes practically impossible to run and one or both rolls must be removed for grinding. Again, there may be overpressing at the edges because the

sheet is always run heavier there to avoid cracking and to even up the caliper of the finished roll; over a period the same unevenness of wear and trouble on the press will occur. Under such conditions as these a frequent grinding cycle will be needed and because of the trouble they give on the press a better solution to avoid the necessity of running in that way should be sought. Softer rolls will also wear more and be more sensitive to differences in load, so that they too will require more frequent grinding.

Apart from the actual magnitude of the camber the shape of the camber curve is very important and presents similar difficulties when it comes to calculation. The original analysis of this problem by S. F. Smith in the Technical Section Proceedings of the British Paper Makers' Association for November, 1936, remains the best source of information on this subject and his formula for the shape of the camber curve is probably the closest that can readily be calculated. Even then the effect of shear stresses within the roll, temperature gradients, and horizontal deflection under the driving stress are ignored, but nevertheless will all influence the shape of the ideal camber to an unknown degree.

The shape of the camber normally imparted by a grinder comes from a circular cam with a slightly eccentric centre of rotation. Rotation of the cam is usually geared to travel with the carriage along the grinder bed and the position of the cam giving the high point is set at the centre of the roll; the precise shape of the curve then depends on the amount of rotation of the cam and hence on the roll length. According to Chatwin (53) rotation of the cam is best set at 70°, though for rubber rolls 90° is better due to movement of the rubber after grinding. Instead of using a circular camber, occasionally what is known as a parabolic camber is put on the roll; however, neither shape corresponds exactly to the curve determined by Smith and the greatest discrepancies usually occur at a distance of between 10 per cent. and 20 per cent. of the roll length in from the edges. It is in these regions that variations in pressure are most frequently noticed in press rolls.

Due to these various difficulties it is common practice to adjust the camber shape imparted with the circular cam by re-grinding selected regions of the roll. This can be a time-consuming task which could only be eliminated by the introduction of special gearing into the grinder mechanism to permit a variety of slightly varied shapes to be available for a given roll length instead of just one shape, so that a better compromise may be achieved. Wear curves can be used to assist in determining the best initial camber shape and the same procedure as for determining the magnitude of the camber, i.e. frequent on-machine checks and the plotting of wear curves, can be used. Greater care needs to be exercised in using wear curves for this purpose, however, and any alterations required to the shape of the curve should be apparent in symmetrical wear of the roll. Localized high degrees of wear should be interpreted with care and only very small changes in shape of the crown made at any one time.

Ideally it would be desirable to avoid having to place any camber on press rolls at all. Apart from all the difficulties of putting on a suitable camber, when a roll has a greater diameter in the middle then the speed of

the surface of the roll is higher there than at the ends. This means that some slippage must occur between the press rolls and the paper will be slightly stretched in the middle. Normally the total camber required is distributed between top and bottom press rolls to give a nip as near horizontal as possible; the precise division of the camber depends mainly on the load applied and can be calculated. It usually amounts to around one third of the total camber for the top roll and the remainder for the bottom. Possibly the best conditions in the nip are not achieved when it is horizontal and a different compromise would allow more satisfactorily for the effect on the paper of the speed difference of the rolls, but such considerations as these are still a matter for controversy. The introduction of such devices as the 'Accra-nip' anti-deflection roll and the 'swimming' roll, which largely avoid the necessity for camber, should solve a great many of these problems once they are perfected for presses; the design and operation of these rolls is discussed briefly in connection with calender camber-compensation.

4C.3 2 Variations in the felt

It is unlikely that faults originating in the felt itself are the cause of many frequent cross-web variations in performance. In most cases these are caused by other parts of the press and are transmitted to the felt. Probably the most common variation from the felt itself comes from unevenness of the seam; in places where the seam takes up the greatest angle to the cross-machine direction the felt weave is most distorted and this has been observed to reduce the porosity and hence the dewatering properties of the felt. If the felt seam can be kept as level as possible across the machine most trouble from distortion of this nature should be avoided.

Any variation in pressure applied in the press nip is eventually transmitted to the felt. If the pressure is higher at one point across the machine the felt will start its life by responding to the higher pressure and taking more water out of the sheet; in time the felt will wear faster at this position and due to the greater quantities of water passing through may become plugged to a greater extent than the rest of the felt. This will have the effect of reducing the ability of the felt to carry water and gradually the greater pressure will have less and less effect until the dewatering efficiency of the press pretty well equalizes all the way across. For this reason any errors in cambering of a roll or in load application should be more noticeable when a felt is first put on the press and will gradually diminish as the felt ages.

A similar effect occurs if one position across the web is consistently different in moisture content or substance when entering the press (this may be accidental due to an uneven condition in the wire part, or it may be deliberate, as for example when the sheet is run heavier in one part to counteract a condition of over-drying which produces a dry streak at the reel-up). If the sheet were continually wetter in one part of the web, the felt opposite that position initially extracts more water and evens up moisture content, but then gradually becomes more plugged than the remainder of the felt due to the greater quantities of water passing through. So the dewatering efficiency of the felt in that position gradually diminishes and the wet streak reappears in the web to a more prominent extent after

the press section. Thus the felt tends to return conditions to their original state: if the cause of the wet streak were accidental in the wire section then it begins to give more trouble again as the felt ages; if the wet streak were deliberate then the fault it was designed to remedy will be more apparent with the new felt and the substance difference would need to be much greater at first.

The moral of all this, as with loading the press unevenly to correct a drying profile error, is that the use of the press to remedy faults elsewhere in the machine is likely to lead to more trouble than it overcomes. This applies especially when deliberate alterations are made to remedy faulty drying conditions and such measures should never be other than temporary until the trouble can be found and corrected.

4C.3 3 Other sources of cross-web variation

There are several other things which can affect the cross-web moisture profile through a press section and most of them are likely to occur in random positions anywhere across the roll. The most common originate in faulty felt cleaning equipment and, in the case of suction rolls, in sealing spray pressure differences across the roll.

Poor cleaning in one or more positions across the felt will obviously allow the felt to become dirtier and more plugged with material so that as it ages a wet streak will become more noticeable. If an uneven roll shower causes more deposits to build up in the holes in one position, then removal of water from the sheet eventually must become inhibited in that region and a similar result occurs over a longer period. In a similar way a fairly permanent difference in substance or moisture originating in the wire section may cause the holes opposite to become more made up purely from carrying the greater quantities of water removed in that position; hence over a long period the press would cease to cloak the fault and the uneven condition of the sheet at the couch would gradually become more noticeable. Some of these differences in moisture content may become so accentuated as to cause breaks at the press because of the difference in adhesion to the top roll, or to cause creasing in the drying section.

If a small patch of holes in the press roll becomes made up, or if the roll itself becomes damaged at one spot due perhaps to something passing through the nip, then the problem is mainly one of reducing the resulting blemish to manageable proportions. If a patch of the sheet is damper entering the drying section than the rest it will shrink slower as the sheet dries; this will cause the patch to become stretched and visible in the finished sheet due to a variation in optical refraction properties. Larger patches will also exhibit cockling. If the patch is markedly damper at the calenders it can become blackened and distorted into wrinkles and possibly stamped out completely.

4C.3 4 General considerations

Enough has been said in the previous sections to illustrate the complexity of the problem of controlling cross-web moisture variations at the presses.

One or two people, notably Chinn (18), consider that frequent and comprehensive testing of the press section involving sampling across the web for moisture tests can help considerably in keeping variations to the minimum. Chinn cites several examples of the effects of various alterations to the press section and mentions one case, for example, where analysis of a press test eventually led to the discovery of a seized dry felt stretch roll!

Unfortunately, analysis of the results of a press test is by no means simple and the interactions between rolls, felt and paper complicate deductions enormously. Certain variations, such as those due to poor cambering, are relatively long-term in their effect and may be discovered from careful comparison of press test data; but other faults some of which show up more at the beginning of a felt life, some towards the end, may completely resist detection. The author considers that, apart from periodic sampling and testing to keep check on the general press performance as a whole and provide suitable standards, comprehensive press tests involving taking many samples from across the web are best kept as an aid to trouble-shooting to help unearth the cause of some disturbing unevenness in profile.

In general, cross-web variations will be kept to a minimum if three ideals are aimed at: keep the substance profile at the reel-up as level as possible (as discussed in Part 1); minimize camber discrepancies by careful analysis of wear curves taken during the life of and before regrinding a roll; and keep the felt seam straight. If despite this variations occur at the reel-up, as they inevitably will, then a detailed press test involving the various techniques that have been discussed may pin down the trouble. But the cross-machine substance must be evened up first and so long as the wire section is reasonably in order variations in press performance due to differences in substance and ingoing moisture will then be minimized and the moisture content figures should be sufficiently representative for the purpose of providing comparison across the web.

4C.4 PRACTICAL POINTS

4C.4 1 Start-up

When starting-up the press section the aim should be to get the general conditions of both press and felt as close as possible to normal before the sheet is actually fed through. This implies that the press as a whole should be well warmed up and approaching the equilibrium temperature attained when running, while the felt moisture content should also be close to its eventual value with the sheet up.

The press section is very often one of the last to be started on the machine. After a check-over to remove any oil or grease and see that the felt is clean and undamaged both inside and outside, the top roll is lowered slightly from the raised position it was left in when the machine was shut and the felt tightened sufficiently to allow it to be driven slowly round. Water (preferably warm) is sprayed onto the felt and, especially if this is done by hose, it is important to maintain an even wetness over the whole

width otherwise the felt may crease; pools of water should definitely be avoided as slack areas may develop later. As the felt shrinks the stretch roll is steadily slackened back to keep the felt tension just sufficient to drive the felt rolls. In some of the newer types of felt, such as the needled or batt-on-base type, the felt may behave rather differently when being wetted out and the shrinkage commonly encountered with woollen felts may not occur.

Shortly before the web is ready for feeding up from the couch the top roll is lowered to near normal running load, the felt is tightened to the usual tension, and the sprays are shut off. By this means each press is brought up to near normal running conditions and the felt is not likely to be so wet that the sheet may tend to adhere to it. The tail is either passed to the first press by hand (perhaps with the aid of a small felt-covered wooden roller to lift the tail off the wire), or it is blown over from the couch onto the first press felt; in the case of a lick-up or suction pick-up, the forward drive roll is raised or the pick-up roll lowered so that the felt touches the paper lightly and carries either a tail or the full sheet over to the first press. The passage of a narrow tail 4 in. to 6 in. wide through one end of the press throws a greater pressure on to it than on the full width sheet so if the tail crushes it may be necessary briefly to relieve the load on the front side. As soon as the tail is running satisfactorily up the top roll, whenever practicable it is preferable before feeding through to the next press or the drying section to widen the sheet using the movable jet cutter on the wire and to even up the press load. If this is done, the vacuum on a suction press and on a felt suction box will come up to the usual level and conditions generally in the press will approach equilibrium quicker so that the paper is less liable to give trouble.

Transfer off a top roll on a slow machine is effected by hand, sometimes with the aid of a lump of wet broke. On faster machines a pair of compressed air jets shaped like the horns of a cow and directed inwards towards each other will draw a tail off the roll while another suitably placed air jet will help to carry the tail over to the next press; these jets require careful setting and should be checked periodically because if they get knocked out of line a great deal of frustration and delay can be caused. For passage through the drying section a slightly wider tail may be cut and this is thrown or blown between the carrying ropes when these are used. A narrow strip of paper often will not stand up to the normal running tension and it may be necessary to slacken back the draws when feeding up the tail to prevent the sheet snapping.

At the earliest opportunity the draws and other press conditions should be checked and reset. If there is difficulty getting the tail off the press roll some dilute vitriol may be dropped onto the roll to reduce adhesion but this is essentially a stop-gap. The most effective way of preventing sticking at the presses is to ensure that start-up conditions in respect of composition of the paper, temperature, and ingoing moisture content are as close as possible to those pertaining during normal running. If the sheet tends to follow the felt it is probably caused by the felt being too dirty and plugged; if the felt is clean a lighter load may temporarily help to reduce this tendency.

361

4C.4 2   Shut-down

When stopping the press section, even for a short time, the top roll pressure should be relieved slightly and the felt examined for plugging and run round with sprays on for cleaning. An acid washing compound may be used on the felt and the addition of small quantities of a neutral detergent can help to remove pitch, rosin and wax deposits. When cleaning equipment rubs on the felt, as with a Vickery conditioner, the shoes should be cleaned of pitch, felt hairs, etc.; it is good practice to do this anyway at least once a shift when the machine is running.

For a complete shut the top roll is lifted completely off to avoid putting a flat on the rolls and the felt tension is relieved. The doctor blades should be cleaned and checked for passing stuff and changed if necessary; the doctor should preferably be left raised off the top roll, particularly if it is heavy. Other parts of the press, such as the suction boxes on the felt, will require cleaning and should be checked for wear.

If the felt seam is uneven it can be squared up, but this is unlikely to prevent it going out of true once the press is started again, particularly if a different nip pressure is used. In the case of a suction press, the holes should be examined and any tendency to make up especially at the ends of the roll should be noted.

4C.4 3   Changing and running wet felts

There are as many ways of changing a wet felt as there are machines. Generally the old felt is cut across after the press rolls and collected behind the top roll doctor or in the pit as the rolls are crawled round. While the new felt is prepared the frame and rolls should be well cleaned down and the stretch roll slackened right back to give a maximum length of felt to play with. The top roll is lifted and locked in position while the bottom roll is cantilevered or slung up allowing the front end support to be removed so that the felt can be slipped over the bottom roll.

Clean paper should be laid on the machine house floor before unwrapping the felt, and the direction of the nap should be checked to see that the arrow on the felt shows the correct direction of running. With two-sided felts a check should also be made that the right side will face the paper. It is useful to arrange for the seam to be near the press roll when the felt is being put over the roll to make it easier to check that everything is right at least after this most difficult part of the operation is complete. The felt is handled easier if the two laps are well separated and plenty of slack is available at each roll.

Finally the seam is straightened out, the stretch roll tightened slightly and the top roll lightly lowered. After a thorough inspection to ensure there are no wrinkles, creases, or dirty patches, the felt is wet out in the manner described in 4C.4 1. In some mills the felt is kept very slack and two members of the crew pull the felt out as it passes into the press nip; this may be advisable when the felt is first wetted but it should not need to be continued for very long if sufficient care is taken to wet the felt evenly. A wetting detergent may be used on a new felt to assist wetting out.

Occasionally the felt will be too wide even when it is thoroughly wetted and even tightening the stretch roll as hard as possible will not bring the width down to a manageable level. In this case, if experience of the particular make of felt indicates that it is likely to shrink appreciably soon after the machine is started, then as a temporary expedient the stretch roll can be slackened back at one side causing the seam to run at an angle to the cross direction and the felt width to reduce. This procedure affects the drainage properties of the felt which will plug much faster if not corrected reasonably quickly. As a final expedient, of course, the felt can be trimmed at the edges.

Once the machine is running it is very important that the seam should be kept as straight as possible. If the seam leads on one side of the machine the indication is that the felt run is shorter there and the stretch roll should be tightened at that side to equalize the length of run. The most common occurrence is for the seam to lead in the middle; this can usually be attributed to the fact that camber on the rolls causes the felt to travel slightly faster in the middle, though when tension is high and felt rolls deflect inwards this also causes the seam to lead in the middle due to the felt having a slightly shorter run in that position. Normally this tendency will be taken care of by having one or two felt rolls with a slightly hollow camber or having a worm roll with the worm only on the edges of the roll; the surface of these rolls then travels at a slightly faster speed at the ends compared to the middle which counteracts the opposite motion caused by the press rolls. Expanding 'spreader' rolls, usually of the fixed-bow type, have also proved helpful for keeping the felt stretched wide and the seam straighter. For further discussion of this topic reference can be made to an article by Woodside and MacMillan (52).

If the camber on the press rolls is higher than usual this will be shown by the felt seam leading slightly more than usual in the middle. When a new roll shows this tendency it may be sufficient as a temporary correction to slacken the felt if it is more tight than usual. Alternatively, on some machines it is possible to put on a string worm at the edges of a convenient felt roll and provided this is done by an experienced person it should give a satisfactory temporary remedy (the string should never become a permanent feature, as often happens). In some mills lumps of wet broke are thrown onto the felt rolls at the edges for the same purpose; this has recently been roundly condemned because it has been shown to cause filling up of the felt and press rolls, leading eventually to reduced dewatering. If the camber on the press rolls is less than usual the opposite tendency will occur, the seam will lag behind in the middle and one of the felt rolls will need building up slightly in the middle. A seam which is uneven but symmetrical across the machine indicates that the camber shape is likely to be incorrect with the camber too great in regions where the seam leads. Associated with wear tests on the press rolls this can give a useful clue to grinding faults.

Felt guides normally require little attention. If the stretch roll is tightened on one side to correct the seam then the felt will tend to run over to the opposite side, which is then slacker. For this reason, whenever the stretch

roll is altered in this way the felt guide should be watched and if necessary the hand guide roll should be adjusted to even up the felt.

4C.4 4 Checking the press during running

Periodically during each shift the machineman will check over the presses. This means that he examines all instrument and recorder readings and when required completes a log. He will have an idea of the normal degree of variation affecting each reading and his interpretations of the instruments will take account of this. Any sign that an instrument reading is out of the normal expected running limits will occasion an inquiry to find the reason; many aspects of this were dealt with in 4C.1 to illustrate the use of different measurements in trouble-shooting.

Apart from this, examination of the press section depends a great deal on the individual design. Attention to the felt has already been mentioned. The press doctor should be checked and if fibre normally builds up slowly on the blade it should show an even rate of movement all the way across the machine. If the build-up is excessive the tray will require frequent cleaning out and the acidity of the stock may require adjusting within the limits normally accepted.

It is particularly important to check that the draws are satisfactory; if the sheet has tightened or slackened, and the mechanics of the press are satisfactory (no belts slipping, etc.), this can often give a useful indication, when interpreted with the position of the dry line on the wire, of changes in substance or freeness. On a plain press the flow of water down the back of the press roll should issue from the nip fairly evenly all the way across the roll, although it is normal for the flow lower down the roll to break into a series of regular streaks. Likewise on a suction press roll sometimes the throw-out from the holes can be seen and this can be a useful indication of the state of the press though it is never possible to see very far along the roll to compare the throw-out all the way across.

Most breaks at the press originate in the wire section. Poor formation, lumps, slime, poor edges, air bells, dandy picking, and numerous other defects can cause trouble at the press where the weakness is shown up either by crushing in the nip or in excessive adhesion to the top roll. Poor substance control, with the sheet coming spasmodically damper to the press all across or in streaks, can cause the same sort of trouble. Likewise, variation in freeness or vacuum on the suction boxes and couch can show up in the same way.

The causes of breaks attributable directly to the press section include the following: unevenness in the draw caused by variation in shrinkage in the sheet itself or by mechanical slippage in the draw control causing the sheet tension to become excessive; felt or suction roll becoming badly plugged so that rubbing and crushing occurs locally or the sheet adheres too strongly to the top roll; felt badly guided and worn at edges or in body so that dewatering is very uneven in places in the nip: press doctor worn unevenly or pitch building up under the blade causing fibre to pass round roll; and air between the paper and felt causing blow-creasing.

364

In addition probably a never-ending list of minor ailments can be thought of, including: water and lumps passing down the edge of the doctor onto the roll and being splashed into the sheet; loose threads from the edges of the felt getting entangled into the paper; condensation water gathering on the back of the doctor and dropping on the sheet; and, in a comparatively dirty felt, too much water carried round from a Vickery conditioner causing excessive crushing and a long ragged hole in the sheet. All these faults are avoided only by a careful supervision and anticipation.

REFERENCES

(1) Dixon, W. B.: 'The Operation of a Stacked Press with Vacuum Transfer on an English Newsprint Machine.' P. and P. Mag. Can. 53, 11, 115. October, 1952.

(2) Hanson, K. F.: 'The Press Felt and its Water Content.' Svensk Pap. 56, 16, 525. 1953. (In Swedish.)

(3) Anon: 'Application of Infra Red Irradiation to the Pre-drying of Paper.' Papeterie 76, 9, 559. 1954. (In French.)

(4) Holden, H.: 'Some observations on suction couch rolls, suction press rolls and vacuum transfer.' Tech. Bull. Tech Sec. Brit. Paper & Board Makers' Assoc. 31, No. 1:7–12; No. 2:41–6. February, April, 1954.

(5) Nissan, A. H.: 'Functions of the Felt in Water Removed on the Papermaking Machine.' TAPPI, 37, 12, 597. December, 1954.

(6) Molsberry, M. V.: 'Modernising a Press System with an Air Bleed Press at Wisconsin Rapids.' Paper Trade Journal 140, 8, 42. February 19, 1956.

(7) Osborn, R. V. and Wicker, D. B.: 'Beta Ray Measurements of Moisture in Running Felts.' TAPPI 39, 7, 480. July, 1956.

(8) Peters, J. H.: 'Effect of Felt Design on Paper Machine Operation and Felt Life.' TAPPI 39, 8, 575. August, 1956.

(9) Fahlin, B.: 'Adhesion of Paper to Press Roll Covers.' Svensk Pap. 60, 13, 484. 1957. (In Swedish.)

(10) Jordansson, L.: 'The Press Section with Vacuum Transfer.' I.—General Operating Conditions and Water Removal. Svensk Pap. 60, 5, 59. 1957. II—Suction Roll Operation. Svensk Pap. 60, 12, 447. 1957. (In Swedish.)

(11) Dixon, P. H.: 'A Comparison of the Operation of Two Wet Felts.' Also Discussion. Proc. Tech. Sec. 39, 2, 173. June, 1958.

(12) Engel: 'Improved Water Removal from the Paper by Resistance Heating.' Woch. für Pap. 86, 22, 953. 1958. (In German.) Summary in Tech. Bull. Tech. Sec. Brit. Paper & Board Makers' Assoc. 36, 4/5, 130. August/October, 1959.

(13) Gavelin, G.: 'Thoughts on Pressing.' Svensk Pap. 6, 11, 345. June 15, 1958.

(14) Grant, J.: 'Summary of Literature on Papermakers' Felts.' Part I—Wet Felts. Also Discussion. Proc. Tech. Sec. 39, 2, 151. June, 1958.

(15) Pollard, D. F.: 'An Operational Report on Sheet Pressing at East Millinocket.' P. and P. Mag. Can. 59, 7, 133. July, 1958.

(16) Anon: 'A New Process for Better Dewatering at the Wet End.' Paper Maker 137, 3, 65. March, 1959. (Translation from Allg. Pap. Rund, November 5, 1957, p. 1077.)

(17) Pallavicini, M. R.: 'How Infra-red Heating is Used to Increase Production at A.P.M.' Paper Trade Journal 142, 26, 36. June 29, 1959.

(18) Chinn, G. P.: 'The Practical Application of Press Testing for Improved Paper Machine Performance.' P. and P. Mag. Can. 61, 5, T-287. May, 1960.

(19) Ford, T.: 'Needled Felts and particularly "Needle Reinforced Felts".' Paper Maker. Annual Review Number, 1960.

(20) Sulatycki, R. W.: 'A Few Thoughts on Paper Machine Pressing.' P. and P. Mag. Can. 61, 3, T-109. Convention Issue, 1960.

(21) Wahlström, B.: 'A Long Term Study of Water Removal and Moisture Distribution on a Newsprint Machine Press Section.' I.—P. and P. Mag. Can. 61, 8, T-379. August, 1960; II—61, 9, T-418. September, 1960.

(22) White, R. and Berdux, F.: 'Static Pressing of Wet Sheets and Felts.' TAPPI 43, 6, 580. June, 1960.

(23) Anon: 'Sulzer Vacuum Installation Proves Highly Successful on Paper Machine.' Paper Trade Journal 145, 6, 41. February 6, 1961.

(24) Grant, D. M.: 'A Preliminary Report on Felt Air Porosity Measurements.' P. and P. Mag. Can. 62, 5, T-289. May, 1961.

(25) Howe, B. I.: 'Towards a better understanding of the Press Section of the Paper Machine.' Paper Technology 2, 4, T-156. August, 1961.

(26) Sweet, J. S.: 'A Basic Study of Water Removal at the Press.' P. and P. Mag. Can. 62, 7, T-367. July, 1961.

(27) Wicker, D. B.: 'Press Felts and Water Removal.' Paper Trade Journal. Part I: 145, 42, 40, October 16; Part II: 145, 43, 33, October 23, 1961.

(28) Anon: 'Newsprint Men Discuss Felts at Conference.' P. and P. Mag. Can. 63, 2, 46. February, 1962.

(29) Gavelin, G.: 'New Approach to Paper Machine Press Sections.' Paper Trade Journal 146, 15, 38. April 9, 1962.

(30) Howe, B. J. and Cosgrove, C.: 'Factors affecting Pressing Efficiency on the High-Speed Suction Press.' P. and P. Mag. Can. 63, 11, T-515. November, 1962.

(31) Radvan, B. and Karpati, D.: 'Adhesion of Wet Paper to Solid Surfaces.' Paper Technology 3, 2, 143. April, 1962.

(32) Redfern, A. P. and Gavelin, G.: 'The Causes of Shadowmarking in Paper.' Paper Technology 3, 5, T-161. October, 1962.

(33) Brandberg, M., Brauns, O., and Swanberg, O.: 'The Wire-Felt Press.' Svensk Pap. 66, 24, 1031. December 31, 1963.

(34) Dyer, H. : 'Plastic Fabrics iron out many Wet Pressing Problems for Mead.' Paper Trade Journal 147, 3, 26. January 21, 1963.

(35) Hamilton, H. D. and Wrist, P. E.: 'The S.P.F.I.—Mead Fabric Press: A Novel Approach to Wet Pressing.' P. and P. Mag. Can. 64, 5, T-219. May, 1963.

(36) Wicker, D. B.: 'Progress Report on the Use of the Felt Porosity Tester.' Paper Trade Journal 147, 49, 28. December 9, 1963.

(37) Delisle, J. C., Garofalo, J. H., and Cooper, S. R.: 'An Investigation into Wet-Press Operation. Part I: Improving Press Operation. Part II: The Effect of Continuous Felt Cleaning on the Papermaking Operation.' P. and P. Mag. Can. 65, 8, T-315 and T-331. August, 1964.

(38) Howe, B. J. and Cosgrove, J. C.: 'A Unified Concept of the Suction Press.' P. and P. Mag. Can. 65, 10, T-424. October, 1964.

(39) Justus, E. J. and Cronin, D.: 'The Vented-Nip Press.' TAPPI 47, 8, 493. August, 1964.

(40) Lyall, J. D.: 'Observed Crushing in Press Roll Nips.' TAPPI 47, 2, 119. February, 1964.

(41) McNamara, S. J.: 'Water Removal Capacity of Running Press Felts.' P. and P. Mag. Can. 65, 12, T-529. December, 1964.

(42) Perry, F. G., Hervey, L. R. B. and Emslie, A. G.: 'Water Removal from Wet Webs by a Porous Nylon Press Roll.' TAPPI 47, 11, 683. November, 1964.

(43) Robinson, W. F. E.: 'The Double Divided Press.' P. and P. Mag. Can. 65, 12, T-550. December, 1964.

(44) Sussman, P. G. and Grimwood, K.: 'Nip Pressure and Gap Tests under Dynamic Conditions using Commercially Embossed Aluminium Foil.' Paper Technology 5, 3, T-59. June, 1964.

(45) Swanberg, O.: 'New Studies point up Potentials of Double Felted Presses.' Paper Trade Journal 140, 44, 35. November 2, 1964.

(46) Tenfält, E. and Wahlström, B.: 'First Report on Scandinavian Experience with Fabric Press.' Paper Trade Journal 148, 8, 38. February 24, 1964.

(47) Wrist, P. E.: 'The Present State of our Knowledge of the Fundamentals of Wet Pressing.' P. and P. Mag. Can. 65, 7, T-284. July, 1964.

(48) Eiderbrant, A. and Swanberg, O.: 'New Fabric Press Development greatly simplifies Operation.' Paper Trade Journal 149, 26, 32. June 28, 1965.

(49) Haller, H. C. and Curtis, D.: 'Shrinkable Sleeve improves Press Section Water Removal.' P. and P. Mag. America 39, 12, 23. March 22, 1965.

(50) Halas, K. K.: 'Finnish Mill Experience with the Divided Press.' Paper Trade Journal 149, 16, 42. April 19, 1965.

(51) McNamee, J. P.: 'A Study of Rubber Covered Press Roll Nip Dynamics.' Part I TAPPI 48, 12, 673. December, 1965.

(52) Woodside, L. M. and MacMillan, H. J.: 'Guiding Felts—which way the right way?' P. and P. Mag. America 39, 50, 35. December 13, 1965.

(53) Chatwin, M. A.: 'Reel Moisture Improvement by Crown Curve Selection.' P. and P. Mag. Can. **67**, 8, T-353. August, 1966.

(54) Eiderbrant, A. and Andersson, W.: 'The Fabric Press and Paper Quality.' Svensk Pap. **69**, 24, 847. December 31, 1966.

(55) Klass, C. P.: 'Garden State gets 47% dryness from new Swedish Press Section.' Paper Trade Journal **150**, 52, 30. December 26, 1966.

(56) McNamara, S. J. and Baxter, M. K.: 'Water Removal with the High-Intensity Nip Press.' Paper Trade Journal **150**, 8, 70. February 21, 1966.

(57) Nordman, L. *et al.*: 'Relationships between Mechanical and Optical Properties of Paper affected by Web Consolidation.' Consolidation of the Paper Web. Transactions of the September 1965 Cambridge Symposium, p. 909. B.P. & B.M.A. Tech. Sec. publication, 1966.

(58) Pye, I. T. *et al.*: 'Structural Changes in Paper on Pressing and Drying.' Consolidation of the Paper Web. Transactions of the September 1965 Cambridge Symposium, p. 353. B.P. & B.M.A. Tech. Sec. publication, 1966.

THE DRYING SECTION
AND CALENDERS

INTRODUCTION

5I In this Part of the book the final stages in the operation of the Four-drinier paper machine are considered. The drying section has the single object of removing from the web of paper water which is left after pressing. The use of steam drying cylinders is a relatively cumbersome method of achieving this end in comparison with pressing, and in terms of steam and power usage, overall maintenance, and floor space, conventional dryers are by far the most expensive part of the process. For this reason a good understanding and regular checking of the drying section are of paramount importance, and it is such aspects that will form the main concern of what follows.

Despite the cost of drying paper by this traditional method, it remains one which is handsomely economic in comparison with other drying techniques. Fluid-bed drying, straight-pass dryers using high-velocity air nozzles, flash drying as used with pulp, dielectric or high-frequency drying in a strong electro-magnetic field, ultrasonic drying, and several other comparatively new ideas involving basically different concepts of drying are attracting increasing attention as possible successors to the common banks of drying cylinders, but for the present there is little indication of a real break-through. These particular techniques and their potentialities will not be considered, (the reader interested in further details may consult articles by Burgess (57) and Luckins (94)). Certain other techniques, in particular high-velocity-air hoods (otherwise known as air caps, forced-convection hoods, and accelerator hoods, but these terms are less expressive of the essential difference between this type of hood and the ordinary type with an extractor fan), infra-red drying, and drying under vacuum, may be used to augment and speed-up the normal process and also, in the case of the first two, have some potential value as methods of regulating the moisture profile across the sheet. These will receive due attention in the appropriate section.

It is commonplace to incorporate in the drying section various other pieces of equipment. Certain of these may be regarded as essential to achieving the desired finish of the paper on machines in which they are installed, and include the M.G. or Yankee cylinder, smoothing press, breaker stack, and sweat roll. Each of these items, particularly the first, will be considered in detail. Other pieces of equipment found in the dryers for a specific purpose are, strictly speaking, not an integral part of the Fourdrinier machine and will not be dealt with. These include the size press, coating press, and various other devices such as the double-roll unit used in the drying section to manufacture extensible paper. Similarly the use of water doctors on the calenders for the purpose of applying colours, starch solutions, wax emulsions, and so forth, for improving surface smoothness and other characteristics of the paper such as oil and scuffing resistance will not be mentioned.

371

5I.1 Moisture in the paper

The moisture content of paper entering the drying section depends very largely on the efficiency of the presses; the economic necessity of having these functioning as close as possible to the point where disruption of the sheet becomes likely has already been stressed. Depending on this efficiency, and on the type of paper being produced, the moisture content is frequently as low as 60 per cent. (1·5 water/fibre ratio) but may be as high as 70 per cent. (2·3) or even 75 per cent. (3·0). At this point it is worth noting that for representing moisture content throughout the drying section the 'wet' basis, i.e. water as a percentage of total weight, is in common use. This is certainly satisfactory for production calculations and as a description of the state of the paper towards the end of the dryers and at the reel-up, but for fundamental work it is frequently better to use the 'dry' absolute basis in which water is taken as a percentage of dry fibre. This latter form of representation permits a better indication of the state and movement of water within the paper during drying. But moisture content percentage values on the 'dry' basis can be a little confusing in that they are able to exceed one hundred; they are, in fact, exactly the same as water/fibre ratios expressed as a percentage. So unless specifically mentioned, all moisture figures will be expressed on the 'wet' basis. Subtraction from 100 then gives another form of representation occasionally used, the dryness or solids content.

At the reel-up the paper may be dried down to as little as 2 or 3 per cent. moisture content though it is more usual, especially on faster machines producing newsprint and kraft grades, to achieve much higher values of around 5 to 7 per cent. When allowed to humidify under standard atmospheric conditions the equilibrium moisture content is invariably higher than that at which the paper is produced, varying from 5 per cent., for some grades of thin tissue up to as high as 10 per cent., and with common values in the 8 or 9 per cent. region. This difference between moisture content at which the paper is produced and at which it stabilizes in air is important from many angles. When sold in reel form on a tonnage basis, the closer the paper is to its equilibrium value the cheaper it is to produce because for every 1 per cent. of moisture lacking in the paper, 1 per cent. of fibre has to be substituted. When required in sheet form the costly separate conditioning process will be necessary for the same reason and also because it reduces disagreeable manifestations of moisture pick-up in the form of expansion and curl of the sheets. Apart from these points the moisture content at which the paper is reeled alters the effect of the calenders, the presence of static, and the apparent strength and other test results on the paper; also, according to the extent by which moisture is picked up so certain qualities, smoothness in particular, can alter appreciably. The difficulties of getting sufficient moisture into the paper at the reel-up are well appreciated yet the consequences of not achieving a reasonable and consistent level are seldom fully realised; this particular topic and the difficulties attendant on its solution will, because of its tremendous importance, be subjected to a particularly close analysis.

CHAPTER 5A

THEORETICAL CONSIDERATIONS

5A.1 REMOVAL OF WATER IN DRYING

The manner in which water is removed from the paper web during drying has been the subject of much interest and speculation over a great many years. This applies especially to the precise function of the dryer felts, a subject that has created a great deal of dispute which on occasions has (somewhat appropriately) become very heated. Although several details remain unsettled it is now possible to give a fairly comprehensive description of the process of drying, at least in a qualitative fashion. The modern theory to be described is the outcome of work by many distinguished investigators, though a really detailed understanding of how water is removed from the web may be said to date largely from the fundamental work reported in a paper by Dreshfield and Han (22).

5A.1 1 Evaporation from the paper surface

When any surface is damp, a continuous interchange of water particles takes place between the surface and the air; as a preliminary to more detailed discussion of the drying of paper it is important first to clarify the mechanism involved in this. The rate of evaporation of water from a damp surface depends basically on the difference between the molecular vapour pressure of the water in liquid form and the pressure of water vapour in the air in the immediate vicinity of the surface. The vapour pressure of liquid water at a free surface is produced by the continual escape of molecules from the surface and is greater the higher the temperature due to the increased speed of movement of the molecules. The pressure of water vapour in air is the partial pressure any vapour exerts in a gas and is dependent primarily on the absolute quantity of water held in vapour form in the air. Evaporation occurs so long as the molecular pressure of the water in liquid form exceeds that of the vapour pressure of air in the vicinity of the liquid, and ceases only when this air is saturated.

A unit volume of air at a particular temperature can only hold a certain quantity of water vapour, at which point it is saturated and any excess of vapour will immediately condense; the vapour pressure at this point is termed the saturation pressure. Below saturation point the vapour pressure is almost linearly dependent on the quantity of water vapour held in the air and decreases steadily to zero in completely dry air. In other words at a given temperature the vapour pressure of air below saturation point is virtually the same percentage of the vapour pressure at the saturation point as the relative humidity; air at 50 per cent. relative humidity has half the vapour pressure of air at 100 per cent. humidity at the same temperature.

The effect of increasing the temperature of air is to increase the quantity of water vapour it may hold before becoming saturated. If air is cooled the

373

opposite effect occurs and a point is reached, the dew point, where the quantity of water vapour actually present in the air becomes sufficient to make the air saturated at the lower temperature and further cooling brings about condensation. This principle is sometimes applied to reducing the humidity of air: incoming air is cooled well below dew point, water vapour condenses out, the air is then re-heated and, as it contains a lower quantity of vapour, will then be drier than formerly.

Thus, even though the actual quantity of water in a given volume of air is unchanged, increasing the temperature of the air reduces the relative humidity and increases the capacity of the air to pick up and hold water. Also the vapour pressure of the water in liquid form at a free surface rises with increased temperature, so the evaporation rate increases. These are the reasons for heating air blown onto the paper in Grewin systems and hoods: to increase the capacity of the air to retain water, and (by transferring additional heat to the paper) to increase the rate of evaporation.

It may have been noted that stress has been placed on the rate of evaporation being dependent on the state of the air in the immediate vicinity of the surface. This is highly important because even a fast moving body carries a thin layer of stagnant air next to its surface and natural evaporation only occurs so long as this layer is not saturated. Once the vapour pressure of the air in this layer has built up to saturation point no further evaporation occurs. For this reason it is vitally necessary to keep air moving over the surface at an adequate rate for evaporation to be continuous. Generally speaking, the faster the rate of air flow the lower is the relative humidity of the air in the layer adjacent to the surface and the greater the rate of evaporation, although a limit is reached when further increase in air flow produces little effect because it makes only a negligible difference to the relative humidity of the layer of air next to the surface. This principle is used to good effect in high-velocity-air hoods.

To summarize, evaporation from an exposed, damp web of paper or felt is improved the higher the temperature of the surface, the lower the humidity of the air in the immediate vicinity of the surface, and the greater the flow of air across the surface of the paper or felt. One further point which will be considered in more detail in the next main section is that evaporation also involves a transfer of heat energy. To vaporize water requires a quantity of heat equivalent to the latent heat of vaporization at the particular temperature involved. This heat must either be provided from an external source (the heat of the drying cylinder or the surrounding air) or from the paper and felt itself, and in the latter event cooling of the surface would occur and this will then reduce the rate of evaporation. In practice under any given conditions a state of dynamic equilibrium is reached in which heat required for evaporation at the surface is balanced by the inflow of heat and the temperatures stabilize; the evaporation rate achieved is thus the result of a number of fairly complex interactions.

Figures 5.1 and 5.2 illustrate the effects described above and refer to some experimental work on evaporation from a damp felt reported by Preston-Thomas and Dauphinee (29).
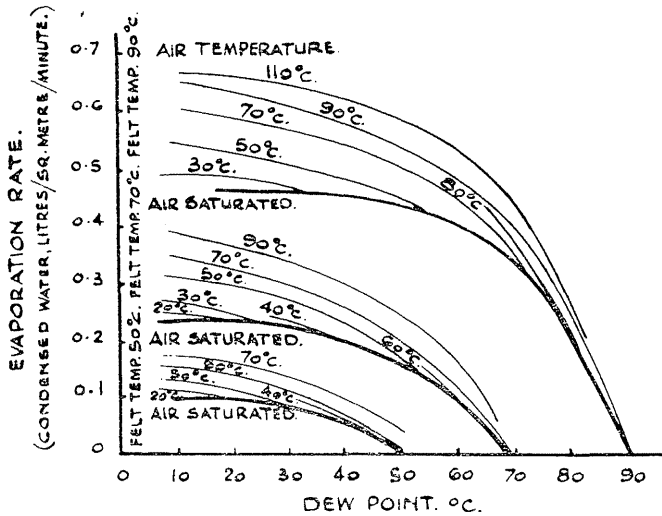
Fig. 5.1. Effect on evaporation rate, from surface of a damp felt at different temperatures, of air temperature and dew point (after Preston-Thomas and Dauphinee)
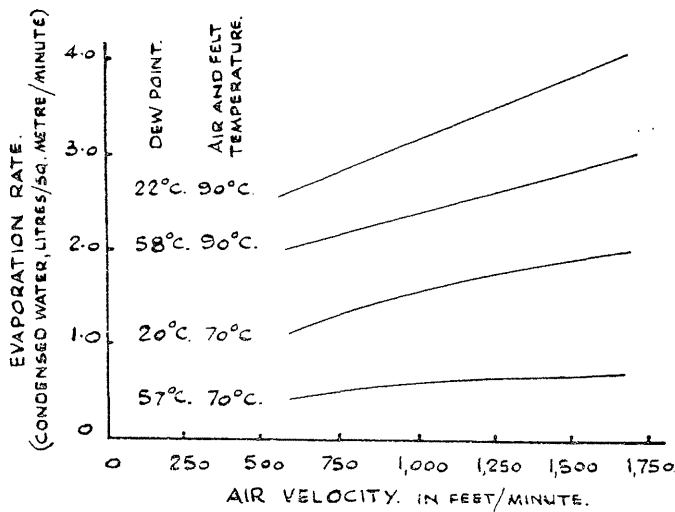
Fig. 5.2. Effect on evaporation rate of air velocity for two air and felt temperatures and two dew points (after Preston-Thomas and Dauphinee)

5A.1 2 Drying on unfelted cylinders

It is proposed first to consider the process of drying on unfelted cylinders. Although few Fourdrinier machines in fact operate entirely without dry felts it is quite common for at least one or two of the early dryers to be left unfelted, so it is appropriate to deal with this relatively simple condition by way of introduction to the subject.

From the moment when the damp web contacts the first heated cylinder (this being often a smaller diameter pony cylinder) a process of heating up begins. Heat is transferred by conduction from the cylinder surface to the contacting surface of the paper web and thence, also by conduction in the initial stage, into the body of the web. In this way a gradient is established between the hotter contacting surface and cooler exposed surface, and the whole sheet rapidly rises in temperature from the region of 70 to 95 deg. F. (22 to 35 deg. C.) up to 140 to 190 deg. F. (60 to 90 deg. C.). As the exposed surface increases in temperature there will be a corresponding increase in natural evaporation to an extent dependent on the condition of the air in the proximity of the sheet, as discussed in the previous section. As evaporation occurs a gradual capillary movement of water within the web will maintain the exposed surface wet.

Even if the temperature of the sheet surface in contact with the cylinder is still below vaporization point when the wrap is completed, in the free draw to the next cylinder there will be rapid evaporation from that surface because it is at a relatively high temperature. This will be accompanied by a drop in temperature of the web as heat is extracted from it to provide latent heat for the evaporated water. On making contact with the next cylinder the new outer surface will still be slightly hotter, but as the web heats up again a reversed temperature gradient, again from the hotter contacting surface to the cooler exposed surface, will be created.

At some position, which is usually very early in the drying section, the temperature of the web is raised to the point where vaporization commences. This will occur at the hottest place within the thickness of the paper, the region in immediate contact with the surface of one of the cylinders. Vapour created in this manner will be under a certain pressure and will pass through the thickness of the web from the contacting surface towards the exposed surface. This takes the vapour into cooler regions of the web, causing a certain amount of condensation and release of heat into the web, while the remaining vapour that is formed at the cylinder surface finally escapes from the outer surface to the air. The heat released in the web by condensation of some of the vapour will augment conduction of heat from the cylinder surface, thereby helping to raise the temperature in layers nearer to the outer surface and thus increase the rate of natural evaporation.

If the web were in contact with the cylinder for a sufficiently long time, as for example with an M.G. cylinder, an equilibrium state is finally reached where the rate of vaporization at the cylinder surface balances the proportion of heat available from the cylinder that is not used to maintain the temperature of the web constant against the loss of heat from natural evaporation and various wasted heat losses mainly in radiation. Numerous

factors such as the air porosity and thickness of the web, the evaporation conditions, and the resistance of heat transfer from the cylinder surface thus affect the drying rate actually achieved.

Water that is vaporized at the cylinder surface must be replaced by capillary movement of water within the body of the web, leading to a gradual migration of water towards the cylinder. Two movements are thus in operation: vapour passing out from the cylinder to the exposed surface, partially condensing on the way, and water moving in the opposite direction within the sheet to fill the pores in the web vacated by vaporized water thereby maintaining the cylinder surface wet. Dreshfield and Han provided

EXPOSED   HOT
SURFACE.   SURFACE.
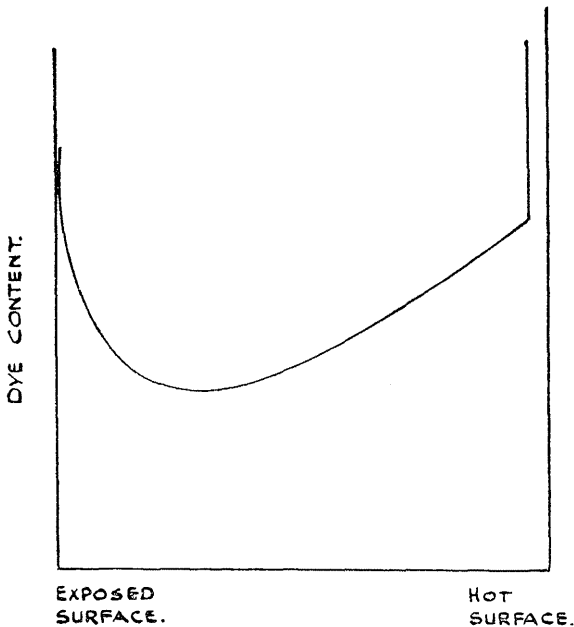
Fig. 5.3. Dye content through the thickness of a sheet dried with one side in contact with a hot surface, illustrating migration of water towards the hot surface (after Dreshfield and Han)

elegant proof of this movement of water within the web during drying by making up laminated sheets with water containing a non-volatile dye so that wherever vaporization occurred evidence of this was left in the form of dyed fibres. Examination of the intensity of dyeing of the different laminates indicated that there was always more movement of water towards the hot cylinder surface than the exposed surface (Fig. 5.3), whereas only movement towards the latter would occur in natural evaporation. Confirmation of this was also obtained with another technique involving the use of beta-ray radiation to determine the moisture content of the different laminates comprising the sheet. Sheets dried completely on

377

one side had a maximum moisture content at a depth of 20 per cent. to 30 per cent. of the thickness below the exposed surface; a condition similar to this may be expected after paper is dried on an M.G. cylinder.

When the paper separates from the cylinder vapour trapped in the inner surface of the web will be immediately released, while at the same time rapid evaporation will occur from the hot surface, accompanied by a drop in temperature of the web as latent heat is provided. Evaporation from the outer, cooler surface of the web will also continue in the draw. Finally the web contacts the next cylinder and the whole process begins again as the new contacting surface of the web is rapidly heated up to the point where vaporization again commences at the cylinder surface.

It is interesting to observe the effect on the movement of water within the web that is produced by the conventional arrangement of alternating cylinders. If the rate of vaporization at both top and bottom cylinders were reasonably balanced, one would expect that there would be a net movement of water from the centre to the surfaces of the web which was approximately the same in both directions. In fact this is unlikely in practice because the cylinder temperatures and heat transfer-rate are frequently different in the top as opposed to the bottom cylinders. Also the resistance to the movement of water at the wire side of the paper is different from that at the top side due to the basic two-sidedness of the sheet; this will produce a difference in the relative rate of migration of water to the two sides of the sheet irrespective of any difference between the rate of drying on top and bottom cylinders.

The difference in migration rate is the reason why when using certain types of dye a colour difference can occur in the finished paper irrespective of any colour two-sidedness due either to preferential dyeing of different constituents of the furnish or to movement within the sheet of pigment dyes. Where sheet structure and substance is varied, differences in the water migration rate in different regions of the web produce a patchy, mottled effect on the colour. Conditions which accentuate the difference in migration rate, such as larger moisture gradients resulting from more rapid drying, may be expected to increase colour two-sidedness originating in this manner.

5A.1 3 Later stages of drying

The rate of drying achieved in the conditions described in the previous section tends to be relatively constant down the drying section. If the cylinder temperatures and draw conditions remain relatively constant, then it is reasonable to expect this. But at some position in the later stages of drying a point is always reached, sharper with some papers than others, where the rate of reduction of moisture in the web begins to fall off. Figure 5.4 (which actually applies to a felted machine but, as seen in the next section, the overall pattern of drying is not affected by the presence of felts) shows a typical drying curve illustrating the very short heating up period, the constant rate of drying, and finally the falling-rate region; the curve is a typical one from several given by Montgomery (11). It should be noted that the moisture results are reported on the 'dry' basis in order to make the

rate of drying equivalent to the slope of the curve (a graph of this type with moisture plotted on the 'wet' basis would be impossible to interpret because the reference point, the total weight of the paper, is constantly altering).

The generally accepted explanation of the falling rate of drying is that it is associated with growing resistance to water movement within the web. As long as the web is sufficiently damp for there to be steady migration of water to the hot surface to replace the vaporized water, this surface will continue to be saturated and conditions of heat transfer and vaporization
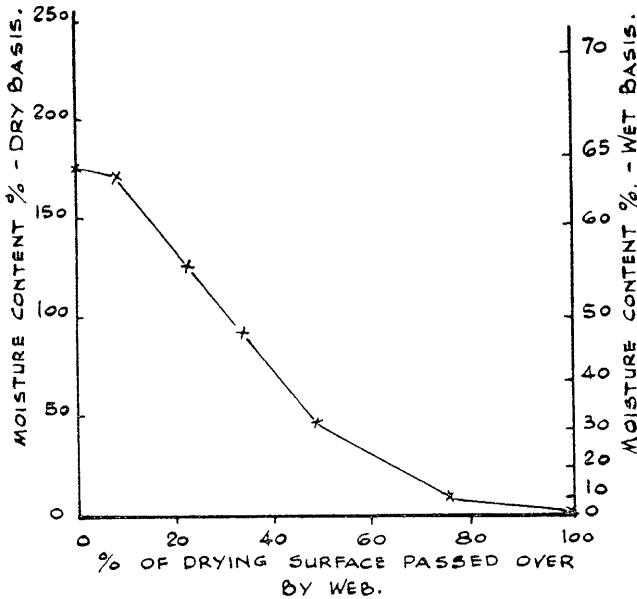
Fig. 5.4. Change in moisture content of a writing paper passing through the drying section (after Montgomery)

remain relatively unaltered. But when a point is reached where the growing dryness of the inner layers of the web acts as a resistance to movement to the surface, i.e. when only finer capillaries within the web remain saturated and thus require a stronger pull to overcome capillary attraction, then the hot surface will no longer remain saturated. The zone where vaporization continues must begin to recede gradually from the cylinder surface into the thickness of the web, leaving paper in the outer layers comparatively dry. As this occurs heat from the cylinder surface has to be transferred through a widening barrier of comparatively dry fibre, so the rate of drying gradually falls off and the overall web temperature increases. In addition to this, water which is held more closely within the pores of fibres is less easy to vaporize than 'free' water which may move along

379

capillaries, and this will contribute to lessening the rate of drying in the final stages. Also, the vapour formed will find it more difficult to reach the surface of the sheet as the continuous network of water capillaries is broken and air intrudes into the web; the vapour must then escape by a process of diffusion rather than by pressure difference through the water capillaries.

The critical moisture content at which the relatively constant drying rate ceases is usually in the 30 per cent. to 45 per cent. region. The precise value must be governed by several factors, but particularly by those which affect the moisture gradient through the web as any increase in this will also cause an increase in the average sheet moisture content at which the hot surface is no longer saturated; Dreshfield and Han obtained some data on this and found that the moisture gradient (and hence the critical moisture content) increases when cylinder temperatures are hotter and also when the sheet is thicker. The lower rate of drying occurring after the critical moisture content has been passed implies that in general the longer this point is delayed, the less total drying effort will be required; as the falling-rate period may begin as early as half way down the dryers, the actual value of the critical moisture content can thus be very important in governing the overall drying rate.

In the falling-rate region of drying, the sheet properties (especially bulk and porosity) are comparatively more important, particularly in their effect on the transfer of heat as the zone of vaporization recedes from the surface of the sheet. External conditions such as the velocity of the air stream and the cylinder temperature are relatively much less critical because there is a lower quantity of moisture removed from the web; the rate of removal of the remaining moisture can only be increased significantly by raising appreciably the surface temperature of the paper.

5A.1 4 Drying on felted cylinders

The essential advantage gained by using a felt is that resistance to transfer of heat from the cylinder to the web is substantially reduced. This much is not in dispute (evidence will be presented later), and with other things equal better heat transfer may be expected to permit faster drying and reduce general heat losses. But with a felt covering the outer surface of the paper the conditions of removal of vapour and of evaporation from the web are appreciably altered; as a direct result of this the net effect of using a felt may not be quite so beneficial.

In considering the process of drying on a felt-covered cylinder, it is convenient to think of four distinct phases. The first phase is the short period during which only the paper touches the cylinder surface, the second phase covers the period when the felt contacts the paper and extends round a majority of the cylinder surface, the third phase is when once again for a short time only the paper remains in touch with the cylinder after the felt wrap is completed, and the final phase covers the period when the web is in open draw between cylinders.

During the first phase the situation is the same as that for an unfelted cylinder. It is of such short duration that no vaporization may be expected in this region, only a commencement of heating-up of the web.

In the second phase the heating-up period is more rapid due to the increased heat transfer; once the process of vaporization at the cylinder surface begins, the movement of vapour and water within the web will proceed exactly as detailed for the case of drying without felts, but with the difference that at the outer surface of the web the vapour and evaporated water must penetrate the felt. The mechanism of this transfer into the felt has been the subject of much discussion and a detailed consideration will be deferred for the moment. Suffice it to say at this point that movement of water into the dry felt may be envisaged in two basic ways: by direct transfer of liquid water either by capillary attraction under the pressure of contact or from migration due to the force of vapour pressure built up within the paper; or by diffusion of vapour into the felt together with partial condensation when the felt temperature is lower than that of the web at the outer surface (the heat released from condensation raising the temperature of the felt and reducing further condensation). During passage round the cylinder, a small proportion of vapour may diffuse right through the dry felt and also some natural evaporation may occur from the exposed surface of the felt if this becomes relatively damp.

During phase three when the felt leaves the web a release of vapour occurs from the separating surfaces of both materials. Evaporation from the surfaces of both web and felt will also be rapid due to their saturation at high temperature. This will be accompanied by a rapid drop in temperature of the inner felt surface and, to a lesser extent, of the paper web which is still in contact with the cylinder. During the short period the paper remains on the web vaporization continues though probably at a lesser rate due to some loss of close contact with the cylinder as the felt pressure is relieved.

In the final phase, the open draw, more vapour is released from the contacting surface of the web as it separates from the cylinder, and the process of evaporation and cooling in air occurs for both paper and felt in the manner already described. As it turns round the felt roll to contact the next cylinder, the felt may approach an equilibrium condition similar to the one existing immediately prior to contacting the first cylinder, but it is more likely that as the felt travels down the drying section its state changes, at least at the surface contacting the paper, and it both heats up slightly and gets progressively damper. The effect of getting damper would be to inhibit further transfer of water from the web and if this were the case the advantages of having a means of drying the felt before it completed its run along the cylinders would be potentially advantageous and might be a strong argument for the use of intervening felt dryers, hot-air drying felt rolls, and other devices. These will be discussed in a later section but it is worth stressing that at the moment little evidence is available to indicate that such progressive dampening of a dry felt does have practical significance; it is more likely to occur early in the drying section with the first top or bottom felts, though obviously it depends on many other conditions in the drying section. One would expect, were drying to deteriorate appreciably as a particular dry felt continued from one cylinder to the next, that there would be a noticeable increase in the rate of drying at the

point where the next felt section commenced; obtaining a complete drying curve through the dryers could therefore be a useful method of detecting this and assessing its importance.

5A.15 The experimental work of Janson and Nordgren

The behaviour of paper and felt through the various phases as described above has been illustrated in detail by Janson and Nordgren (35) and some of their results will now be quoted. This work was undertaken on the Swedish Central Laboratory experimental machine and involved studying the drying of paper over a small felted M.G. cylinder with an associated felt dryer. The moisture content of the paper entering the M.G. cylinder could be altered by varying conditions in some pre-dryers; after-dryers enabled the final reel-up moisture to be kept constant. The most remarkable feature of the work was devising a means of continuous measurement of the temperature both of the dryer at different distances from its surface, of the felt, also at different depths through its thickness, and at the surface between the felt and the paper web. This was achieved with thermocouples embedded in the dryer and felt and placing ingoing leads to the junctions in such a way that each in turn could be connected to a recorder from which a curve showing temperature variation through an entire cycle could be obtained.

Figure 5.5 shows the temperature variation of the paper, and of the felt at depths of 1, 3·5 and 6·5 mm. from the contacting surface (the felt was approximately 8 mm. thick). As each of the phases is passed the behaviour of temperature can readily be interpreted in the light of the description in the previous section. For instance although the web temperature will begin to rise on contact with the cylinder, the rate of rise is increased enormously once the felt touches the cylinder at the beginning of phase 2; this illustrates the important benefit of the felt in improving heat transfer from the cylinder. The web temperature flattens off towards the end of the cylinder wrap as equilibrium conditions of vaporization and water transfer to the felt are approached, but then falls with reduced contact and increased evaporation when the felt leaves the cylinder in phase 3. The drop in temperature when the paper itself leaves the cylinder in phase 4 is extremely rapid.

The temperature of the felt closest to the paper surface varies appreciably, showing a substantial rise while wrapping the cylinder, a fall as evaporation occurs in the open draw, followed by a rise in temperature on the felt dryer and a further fall afterwards. The same pattern can hardly be distinguished at all further into the felt towards the middle, while the outer surface of the felt shows little alteration in temperature at all. The implication here is that there is little or no evaporation and diffusion of water vapour through the dry felt; it is only at the contacting surface that the felt is affected significantly. A further point of interest is that temperature rise on the felt dryer is at a much lower rate than on the M.G. cylinder, despite the fact that the surface temperature of the felt dryer was higher than that of the M.G. cylinder; this is due essentially to the difference in heat

transmission when this is purely by conduction, as on the felt dryer, and when augmented by the transfer of water vapour from the wet web.

While the temperature curves shown in Fig. 5.5 are stated to be fairly characteristic of a number of runs in that their general appearance was always retained, observations taken over a range of various conditions showed up some important and interesting variations. The effect of such factors as the type of felt used, felt tension, machine speed, and steam pressure were all investigated and reported either by Janson and Nordgren
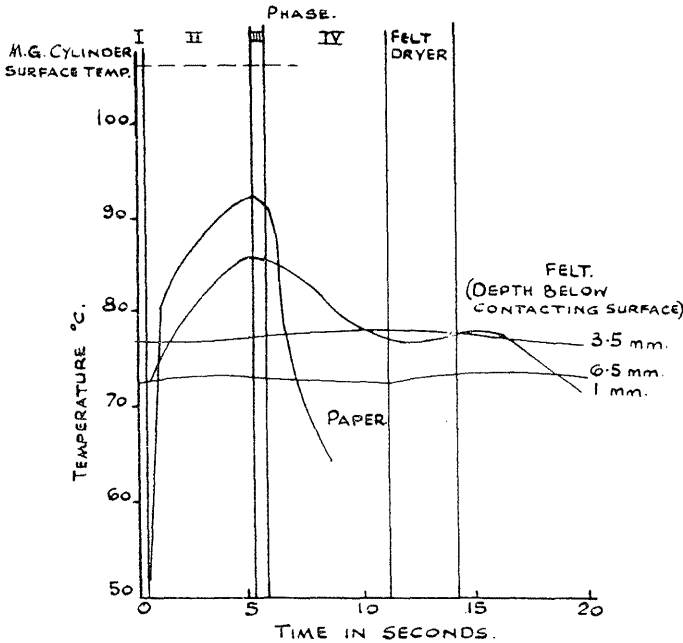
Fig. 5.5. Variation in temperature of paper and of felt (at different depths) round an M.G. cylinder and felt dryer (after Janson and Nordgren)

or by their colleagues in later papers; these will be dealt with later. For the present it is worth examining the results obtained when ingoing moisture content of the paper web and the amount of felt wrap round the M.G. cylinder were varied as these serve to illustrate further the process of drying as detailed above.

Figure 5.6 shows the effect of ingoing paper moisture content on the pattern of temperature rise of the paper on the M.G. cylinder. At high ingoing moisture content there is a tendency for the temperature during the heating up period to increase to a higher level before the curve begins to drop away as equilibrium conditions of vaporization and water transfer are approached. This is primarily because the moisture content and

383

temperature of the felt would be initially higher under these conditions due to the overall higher rate of transfer of water from the paper, and this would force the paper web temperature to adopt a higher value before transfer of water (and thereby heat) from the web commenced. But the rate at which the rise in temperature then drops away is much greater at higher
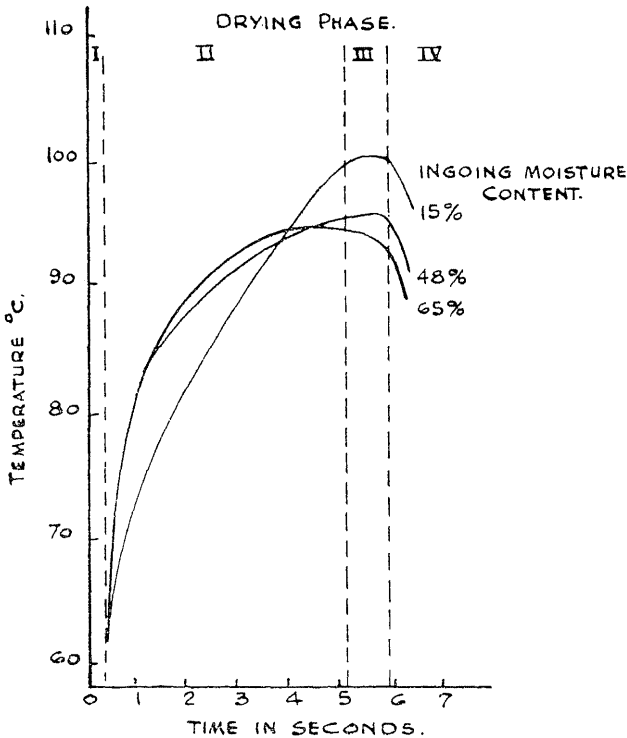
Fig. 5.6. Dependence of temperature of paper over drying cylinder on ingoing moisture content (after Janson and Nordgren)

ingoing moisture contents and the ultimate web temperature in fact approaches closer to the cylinder surface temperature when the web is initially drier.

Using the same experimental set-up Brauns and Ponton (40) investigated the effect of varying the run of the felt and arranged that it left the M.G. cylinder at three different positions giving wraps of 3·8, 2·5 and 0·8 metres, compared to the paper wrap of 4·4 metres. In this instance ingoing moisture content of the paper was kept steady at about 40 per cent. The results indicated an evaporation rate (including the free draw of the paper) of 83, 73 and 70 kilograms per hour respectively for the three degrees of wrap, showing conclusively that it was preferable to have the felt wrap as large as possible. But it may be noted that the difference is not so great as

might be expected, though there is no evidence that the rate of drying was significantly decreased by the growing moisture content and temperature of the felt as it progressed round the cylinder.

5A.1 6 Transfer of water from paper web to felt

In 1954 and 1955 Nissan and Kaye (12, 19) presented some theoretical calculations based on heat transfer considerations that have sparked off a controversy that is still not satisfactorily settled. However, there is now sufficient evidence to put the matter in perspective and show that in practice the issue is not likely to be of any real importance anyway.

What Nissan attempted in the first place was to calculate how much water would be removed from the paper web on the assumption that the felt does not absorb any water and in fact retards drying by restricting evaporation from the web to 10 per cent. of what would occur if it were not present. Calculation of the water that would be removed on this basis produced a result that was too small to account for the actual rate of drying, certainly on slower machines, and Nissan therefore concluded that a substantial transfer of water from the paper web to the felt must occur. As the actual water removal in this phase is greater than it would be in free air it appeared that a percentage of the transferred water must be in liquid form, i.e. by direct migration of water from the web to the felt, rather than by means of transfer in vapour form followed by subsequent condensation.

Nissan concluded from these results that liquid absorption of water into the dry felts was an all important function of the felt (hitherto the general feeling was that the felt served only to improve heat transfer from the cylinder to the paper web), and that this form of transfer was more effective for some reason on slower machines. Following from this he considered that dry felts (especially the first pair) should be constructed on the paper side to encourage liquid absorption, i.e. be soft, bulky, with a good nap, and made of wool, while retaining adequate strength and dimensional rigidity; also the felt should not be allowed to get too damp (or this would inhibit liquid transfer) so that intervening felt dryers or even the use of a drying cylinder for the felt rather than the paper should be considered.

The conclusion that some reduction of moisture content of the paper occurs actually on the cylinder in addition to evaporation in the free draw is not disputed nowadays and several workers have confirmed this, e.g. Soinenen (25), and Janson and Nordgren in the experimental work described above. The actual proportion of the drying occurring in the two phases is known to vary with the machine speed and, as will be discussed in more detail in 5B.6 1, increasing the speed reduces the actual proportion of drying on the cylinder in favour of loss of moisture in the open draw. But the second conclusion reached by Nissan, that a significant proportion of drying on the cylinder occurs by direct migration of liquid water, has been hotly disputed.

Nissan and his colleagues have elaborated this theory (24, 54, 79) and reported confirmatory evidence obtained from measurements on a slow paper machine (27, 32) and in laboratory experiments (on drying muslin, not paper(54)). In the machine work, samples of the paper were drawn

from between the cylinders and the general conditions of drying over the whole section were determined; being a very slow machine (120 f.p.m.) in this case most of the water was shown to leave the paper web when in contact with the cylinders and consideration of the evaporation conditions indicated that some of this must have transferred to the felts in liquid form.

Brauns and Ponton in their work on the Swedish experimental machine referred to earlier, used the comprehensive data available for cylinder, sheet and felt temperatures, steam and air conditions, and steam consumption to perform heat energy and mass transfer calculations in three different ways; each of the three methods gave a good correspondence and indicated that the proportion of water transferring from the paper web to the felt in vapour form was approximately twice that in liquid form. These authors considered that this liquid migration was probably partially by capillary effect (only when the felt is comparatively dry, transfer to a damp felt is hardly possible in view of the relative capillary sizes being so much larger in the felt than the paper) but mainly the liquid transfer was a result of the pressure within the sheet created by the expansion of air and steam.

In a later paper, Ponton (77) also points out that, despite the comparatively low temperature of the web entering the dryers, appreciable evaporation often begins immediately on the first cylinder and the rate of drying is hardly less than in subsequent dryers, even though the web is still largely being heated up at this stage. Exceptions to this are when no felts or felt dryers are used. These considerations support the occurrence of liquid transfer to the felt at the beginning of the dryers.

Aligned against this formidable weight of evidence are the results reported by Kirk and his colleagues (92). This work was designed specifically to obtain experimental evidence as to the nature of the water transfer without relying (as all the results reported above do) on calculations which are dependent on various assumptions, particularly with regard to heat transfer coefficients. Kirk used an experimental apparatus designed to simulate drying (similar to that used by Smith and Attwood (1, 7) to be described later) with three different types of felt: wool, terylene, and reinforced cotton. Handsheets were made from water containing a 1 per cent. solution of potassium chloride which is non-volatile, i.e. water removed from the sheet by vaporization would leave the chloride content of the sheet unchanged. By using a carefully standardized extraction technique Kirk was able to determine the chloride remaining in the sheet after drying and compare this with the known water content of the undried sheet; any drop in the total chloride recovery would indicate liquid transfer.

Over a wide range of conditions (including different felt pressures, substances of paper, dryer temperature, etc.) in no single case was any evidence found that the least liquid transfer had occurred. Composite sheets showed a net movement of water between the laminates towards the hot surface, as found by Dreshfield and Han, but again no liquid transfer to the felt. On a small experimental paper machine similar work indicated that on the first cylinder no more than 0·2 per cent. of water passed into the felt in liquid phase, a result hardly significant. The implications of this

work are that to all intents and purposes water is removed on the drying cylinder only by the vapour transfer mechanism. The nature of the felt itself is only of secondary importance (Kirk draws attention in this respect to the small difference in performance found between a wide range of felts tested by Smith and Attwood) and should preferably be relatively porous to allow as little restriction to the passage of vapour as possible.

What happens on operational paper machines remains undecided. But a reasonable assessment of the situation is that when liquid transfer does occur (as it is known to on occasion because dry felts can become coloured from the paper dyes) it will only be likely to any significant extent over the first and possibly second cylinder, and then only on relatively slow machines where the moisture content of the web entering the dryers is very high. With regard to the desirable properties of dry felts, the possibility of some liquid transfer in the first top and bottom positions must be kept in mind, but by and large other considerations weigh more important.

5A.2 PERFORMANCE OF THE DRYING SECTION

The previous section has described the manner in which water is removed from the paper in the dryers. Attention is now turned to another important aspect of the section, the overall rate at which the paper is dried and the general performance of the dryers with regard to the efficiency of utilization of the heat provided in the steam.

5A.2 1 Transfer of heat to the paper

The amount of heat transferred from a drying cylinder to the paper at any given position is dependent on two variables, the temperature and condition of the steam in the cylinder and the temperature of the paper contacting the surface of the cylinder. For the purposes of the present discussion it is assumed that unpolluted dry saturated steam is used (use of superheated steam is mentioned in 5B.1 5), so that temperature and pressure of the steam are precisely related.

Suppose, for example, that saturated steam in the cylinder is at a pressure of 6 p.s.i.g. or 230 deg. F., while temperature of the paper at the surface of the cylinder is 150 deg. F. Then the rate of heat transfer will be determined by the difference between these temperatures, i.e. 80 deg. F., in relation to the overall resistance to transfer of heat between the inside of the cylinder and the paper. This resistance may be considered to be the sum of the resistance of each intervening layer comprising: (i) the condensate film on the inside of the drying cylinder; (ii) scale or rust on the inside of the cylinder surface; (iii) the metal of the cylinder; (iv) scale and fuzz on the outside of the cylinder; and (v) air between the outer face of the cylinder and paper. Not a great deal is known about the resistances to heat transfer offered individually by these different layers but it is generally considered that (i) is small unless rimming of the condensate occurs, (ii) is relatively small, (iii) is also relatively small except for thicker-walled M.G. cylinders, while (iv) and (v) together account for a considerable portion of the total resistance. In the example, resistance in each layer might be (i)

387

0·0005, (ii) 0·0013, (iii) 0·003, and (iv) and (v) together 0·02, each figure being expressed as the reciprocal of B.t.u. transferred per hour per sq. ft. per 1 deg. F. difference. Total resistance would then be the sum of these, i.e. 0·024, and heat transfer equal to 80 × 1/0·024 = 3,300 B.t.u. per sq. ft. per hour. The temperature at the junction of the condensate film and inside of the cylinder would thus be only a fraction under the cylinder steam temperature at 230 deg. F., the temperature of the inner and outer metal surfaces of the cylinder about 226 deg. F. and 216 deg. F. respectively, and the biggest temperature drop would be between the outer cylinder surface and the paper at 150 deg. F.

If this supply of heat were just sufficient to balance the rate of evaporation and heat losses, then the temperature of the sheet would remain in equilibrium at 150 deg. F. In fact, of course, such a state of affairs is only likely to be attained at the point on a drying cylinder where the paper has been heated to a maximum stable temperature, if such a point is ever reached. At most of the positions round the surface the flow of heat from the cylinder (though governed always by the gradient pertaining at each instant) will exceed that used for evaporation and heat loss, so that the sheet and felt will be heated up in the manner described earlier. As the temperature of the sheet next to the cylinder rises, so the heat transfer will diminish.

5A.2 2 Heat balance for the whole drying section

Under steady conditions, the steam pressure used for drying the paper at any instant may be said to give a rate of heat transfer through each cylinder which is just sufficient under prevailing conditions to evaporate water from the paper down to the desired reel-up moisture content; in other words, the supply of heat meets the demand. What is the situation if, for some reason, the paper enters the drying section containing more water? In this event more heat is required both to heat up the sheet and evaporate the additional water.

Even if the steam pressure in the cylinders is unaltered, it is interesting first to note that more heat is in fact provided automatically to the drying section. Thus, because the sheet contains more water entering the dryers it will not in the early stages of the section heat up quite so quickly; the sheet temperature will be lower at any position round each cylinder than previously in the same position, so it follows that the rate of heat flow will, overall, be greater until the sheet reaches the normal drying temperature associated with the 'constant' rate period. Again, although other things being equal the drying rate in the 'constant' period must be the same in both cases, the point along the dryers where the zone of vaporization recedes into the sheet and the drying rate falls off must be reached later when initially there is more water to remove; in other words, the relatively higher heat flow associated with the 'constant' rate period will extend over a greater number of drying cylinders. It is for these reasons that in any drying system there is an important built-in automatic correction for fluctuations in the moisture content of the paper entering the dryers. Variations in heat demand in the drying section are to a great extent taken care

of without the need for any instrumentation. This is perhaps as well, otherwise it is doubtful whether many machines could run at all.

Further consideration indicates, however, that only a limited automatic compensation for variations in sheet condition entering the dryers may be expected. It can be shown that the extra heat transferred will only partially provide the heat required to remove the additional moisture. The inevitable result is that the moisture content of paper at the reel-up rises, even though only slightly, whenever the sheet entering the dryers contains more water.

A further and more important effect in an uncontrolled drying system is that with greater heat demand the steam pressure does not, as assumed above, remain constant. It will in fact gradually diminish and this, by reducing the temperature inside the cylinders, inevitably reduces the heat transferred to the paper and brings about an even greater increase in moisture content at the reel-up. Such a situation is very easily overcome by provision of a simple control system in which measurement of the steam pressure or temperature in the main section of cylinders is used to regulate the opening of the main supply valve. More will be said about this later but it may be noted at this point that such a regulator is superior to the uncontrolled system simply because it provides a straightforward method of preventing the steam pressure from falling in the wake of an increase in demand for heat; the supply valve is automatically opened to maintain the pressure and provide more steam instead of remaining in a fixed position.

A final example of the relation between supply and demand of heat which may be cited is the situation when a break occurs at the wet-end of the machine. As there is suddenly no web on the dryers, the dry felts contact the cylinder surface directly and, despite the greater resistance to heat transfer across the cylinder/felt interface, immediately begin to heat up and dry out. An equilibrium state would be reached only when the felt temperature (and even more so the cylinder surface) approached that of the steam temperature to an extent which reduced the temperature gradient and hence the flow of heat to the relatively small amount needed to counteract radiation and convection losses. Even though the overall resistance to heat transfer is greater without the paper, the result would be that the dry felt became extremely hot with the risk of scorching. This is the reason why it is always necessary during a break to reduce the steam temperature and on modern steam control systems this is provided for automatically. The extent to which the steam temperature is reduced depends on several factors which will be discussed later; apart from keeping down the cylinder surface and dry felt temperature to prevent damage to the dry felts, the situation when it comes to feeding up the sheet is also of considerable importance.

5A.2 3 Relationship between steam pressure and drying rate

The steam pressure in the cylinders necessary to dry the paper to the desired moisture content is widely regarded as an indication of how well the section is operating. If when running a familiar grade it is found that a much higher pressure than usual is needed to dry the paper, then it is suspected either that the paper is too damp entering the dryers or that

waterlogging or some other trouble in the section is occurring. This, taken by and large, is perfectly sound reasoning, but care needs to be taken in relying too much on steam pressure as an arbiter for whether the drying section is working efficiently. The reasons for this will now be discussed.

At any particular time the average steam pressure provides a temperature inside the cylinders giving an appropriate heat transfer rate to dry the paper. Should the heat demand increase appreciably (such as when speed is increased or a heavier substance is run at the same speed, i.e. well beyond the bounds where automatic compensation of supply takes place to meet variations in demand, as discussed in the previous section) then maintaining the same steam temperature in the cylinders will not give an adequate heat flow and the paper will reel too damp. To overcome this the remedy is, of course, to increase the steam pressure: for the same or possibly slightly higher average paper temperature a greater temperature gradient is established and the overall heat flow increases, providing the additional energy needed for drying. In the same way, increased steam pressure is effective in compensating for a substantial increase in moisture content entering the drying section, or for an increase in resistance to heat transfer occasioned by waterlogging of cylinders; hence the dryerman's usual interpretation when he finds a higher steam pressure necessary is in general perfectly sound.

But there is an important distinction that should be made between high steam pressure necessitated by excessive moisture entering the dryer section or by waterlogging of cylinders, and this shows up in the difference in flow of steam for the two situations. Where the presence of more water to be evaporated from the paper is the reason for a higher drying pressure being necessary, then the effect of this higher pressure is to produce an increase in the average temperature gradient between the inside of the cylinders and the paper and hence in the flow of heat. The additional heat used in this way must be provided by the steam. Within a fairly normal working range the heat given out by condensation of unit weight of saturated steam is practically independent of the pressure (actually, being equivalent to the latent heat, the heat given out decreases slightly with increasing pressure). So effectively the additional pressure used for drying will in this case be reflected almost exactly by a corresponding increase in the flow of steam to the cylinder section.

But in the case of waterlogged cylinders, the increase in steam pressure is required purely to overcome the greater resistance to heat transfer within the cylinders. In other words, to achieve the same rate of drying a greater temperature gradient is needed and this is achieved by increasing the temperature within the cylinders. No increase in flow of heat occurs, and hence the steam flow remains unchanged (actually there would be a very slight increase to offset greater radiation losses from the feed-pipes and sides of the drying cylinders).

Increase in steam pressure is thus not of itself an indication of greater usage of steam. However, as a corollary to this, if knowledge of the steam flow is available in addition to the pressure then the general source of any change in demand (i.e. the paper or the dryers) can be more easily identified.

A steam flow measurement is thus very useful for indicating whether or not the drying rate has altered with the steam pressure.

A further point worth noting is that apart from small changes in extraneous heat losses, there is no reason to expect that the performance of the drying section, i.e. the quantity of steam used compared to the water evaporated from the paper, would alter in either of the two situations just considered. This brings in a further aspect which deserves some consideration.

When cylinders are waterlogged it will be said that the dryers are inefficient. So they are, but not in the sense that steam utilization is poorer. The meaning here is essentially that greater pressure is needed to accomplish the same rate of drying. On many machines the pressure available is limited due to the necessity to prevent the back-pressure of power-generating turbines exceeding a fixed value. In such cases reduction of the heat transfer rate by waterlogging may limit production because the machine is already run with practically the maximum steam pressure available and this is effectively the governing factor determining the machine speed. This is highly important, more so than the relative efficiency of steam utilization, and it is justifiable in such cases to think of the performance of the drying section as dependent on the steam pressure needed to keep up normal production. But it must be realized that this assessment of performance applies essentially to changes in the heat transfer resistance between the cylinder and paper. The correct measure of performance of the dryers refers to how efficiently steam is utilized, and this aspect will now be discussed.

5A.2 4 Efficiency of steam utilization

The performance of the drying section of a paper machine at any particular time is assessed by determining the weight of steam which is used to remove a unit weight of moisture from the web. To calculate this figure it is necessary to measure the flow of steam to the machine, including any supplied for felt dryers and air heating (though the latter may be treated separately); strictly speaking any steam used in calenders, where the purpose and effect is not to remove moisture, should be excluded. Also the average moisture content of the web entering and leaving the dryers must be determined. For practical purposes the moisture content at the reel-up is usually taken as equivalent to that leaving the dryers; if a sweat roll is in use moisture at the reel-up may be taken only if the moisture added to the paper after the dryers is determined or allowed for separately.

The water removed from the web is calculated (in British units) as $(M - m) / (100 - M) = (d - p) / (1 + p)$ lbs. per lb. finished paper, where M, m are the moisture content (wet basis) entering and leaving the dryers, and d, p are the water/fibre ratios entering and leaving the dryers, respectively. This figure multiplied by the production, determined for the relevant speed, deckle, and substance in the usual way, gives the total water evaporated per unit time (a value which is, incidentally, of use in assessing ventilation conditions) and this is then compared with the lbs. of steam used in the same unit of time.

Performance calculated in this way gives a useful measure of the efficiency of steam utilization. The figure obtained depends on the type and substance of the paper and its moisture content entering and leaving the dryers, but is relatively independent of the steam pressure used. Dependence on the paper itself occurs because the heat energy required to dry the web is a function of the structure and thickness of the paper. Dependence on the moisture contents occurs because it is easier to remove additional water in the web entering the dryers than to remove the same quantity of water at the end of the dryers. Some dependence on the steam pressure arises due primarily to the lower latent heat associated with higher pressures, and also because greater heat losses must be expected at higher operating temperature, but unless the range of pressure is wide this should not be very significant compared to the accuracy it is possible to achieve when determining the performance figure. Despite the various factors affecting the result, for any particular grade made on a paper machine the straightforward determination of steam utilization efficiency in the way detailed above is of use for evaluating alterations to the drying or ventilation conditions of the machine and for detecting long-term trends in performance.

With regard to the evaluation of alterations to the drying section it is appropriate at this point to emphasize the importance of using a performance figure relating the water evaporated to the steam used rather than, as is frequently the case, relying solely on the steam pressure to indicate whether an improvement has occurred as a result of making the alteration. The argument that if a drop in steam pressure occurs for similar running conditions then this indicates an improvement is not always true. Certainly, on a machine with limited drying capacity, an increase in production would be likely to follow and under such conditions this will probably be an all-important consideration. But with regard to the performance or efficiency of the drying section it is quite possible for an alteration to bring about a drop in the steam pressure and at the same time an increase in the weight of steam needed to evaporate unit weight of water from the paper.

This may happen (to take a hypothetical example) if a new type of felt were used which allowed a greater tension to be applied by virtue of constructing the felt to be very dense and non-porous. The greater tension could reduce heat transfer resistance at the cylinder/paper interface to such an extent that even with a lower temperature gradient between the inside of the cylinder and paper there is a greater heat flow. Thus, a situation might arise where the denseness of the felt considerably inhibited transfer of vapour from the web to the felt on the drying cylinder, necessitating an overall higher temperature of the paper to achieve the same drying rate, but with the result that the greater heat flow demanded for this could be supplied at a lower steam pressure. Performance in the sense of steam utilization efficiency would therefore be poorer despite the drop in steam pressure.

A second and simpler example of a situation where lower steam pressure resulting from an alteration to the drying section may be less efficient could arise when steam is newly used for heating of air supplied to the section. A

greater rate of drying is achieved because of improved evaporation in the open draws, so for the same production there would be a lower steam pressure in the cylinders. But the overall consumption of steam related to the water evaporated may, as a result of the extra steam used for air heating, be significantly greater.

5A.2 5 Comparing performance with other machines

Apart from the use of performance or steam utilization efficiency figures to keep a long-term check on the drying section of a particular machine, or to evaluate alterations to the machine, it is also instructive to compare the figures with those obtained on other machines making similar grades of paper. Unfortunately the difficulty here is that little reliable information is readily available. A detailed analysis of data provided in answer to a carefully standardized questionnaire circulated to a large number of Canadian mills making newsprint has been reported by Snider (30), and in this close agreement was found over a wide range of conditions between the lbs. of steam used on a machine and the lbs. of water evaporated from the paper, the average slope of the curve, i.e. the ratio between the two, being 1·76. Variations from this figure on individual machines would indicate a relatively higher or lower steam utilization efficiency than average. Snider also pointed out that extrapolation of the accumulated results indicated that a significant evaporation would occur at zero steam consumption, so that relatively higher utilization efficiency figures may be expected on lower speed machines.

There is little similar data relating to other grades of paper and this is partly due no doubt to the relative paucity of steam flow instruments on individual machines. But another form of comparison between the performance of different machines making the same grade of paper which can be useful is the overall rate of drying (commonly known as the evaporation rate); this figure when related to standard data for the grade of paper in question may be particularly useful for giving a clue as to the likelihood of improving the capacity of a machine where the production is limited by the drying section. The evaporation rate is usually determined by relating the total water removed from the sheet in unit time (determined as above) to the area of dryer capacity in use. The latter figure for convenience includes the whole area of each drying cylinder (together with felt dryers) within the width of the sheet, not just the area wrapped by the paper which is assumed in practice to vary relatively little from one machine to another.

The evaporation rate depends very closely on the steam pressure (see Fig. 5.7 which is from the same report by Snider relating to newsprint; similar curves for other grades of paper may be found in the TAPPI Data Sheets). This dependence is, of course, due basically to the fact that, other things being equal, the rate of drying depends on the rate of heat transfer and this is greater for a higher steam temperature. Also the evaporation rate is dependent on the moisture content entering the drying section; the greater this is the higher will be the evaporation rate, and under such a condition the capacity of the dryer part would appear better than it actually was.

Another form of comparison is to use the straightforward production figure instead of the water evaporated and to calculate steam utilization efficiency or the drying rate on this basis. The spread of results for different machines then tends to be wider because variations in moisture content
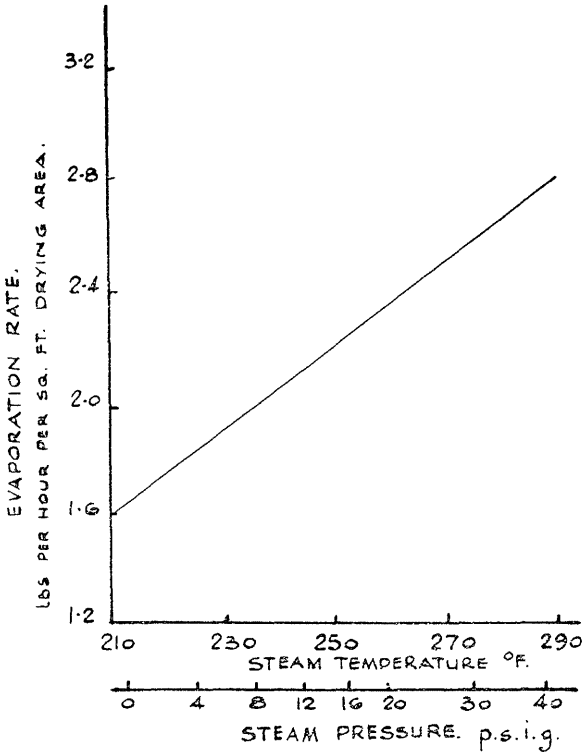
Fig. 5.7. Evaporation rate for newsprint related to steam pressure in the drying cylinders (after Snider)

entering the dryers exert a relatively greater influence. Information on drying rates based on this method can also be found in the TAPPI Data Sheets for different grades of paper.

5A.3 EFFECT OF DRYING ON PAPER PROPERTIES

Although the purpose of the drying section on a Fourdrinier machine is essentially to remove water from the paper web, it has long been recognized that the manner in which this is accomplished has an important effect both on the behaviour of the web during the drying and on the characteristics of the finished paper. The key to these phenomena lies in the relationship between two fundamental properties: the amount of shrinkage in the web

394

which would occur naturally as the paper dried, and the amount of shrinkage which in fact is allowed to take place on the machine.

It is proposed in this section to discuss first the nature of shrinkage in the drying section. The effect on the final properties of the paper of this shrinkage, and of its restriction during drying, are then described together with other phenomena associated with the drying process, such as cockling and curl. A brief discussion is also included of the factors affecting the moisture content of paper in equilibrium in air, and the influence this has on the properties of the paper.

5A.3 1 The nature of shrinkage

The basic source of shrinkage of the web is the shrinkage of individual fibres comprising the web. Surface tension forces are responsible for some of the overall contraction in the earlier stages of drying, but these alone could not account for the manner and magnitude of the shrinkage commonly observed. But even though the origins of shrinkage are thus clear, the manner in which the contractions of individual fibres affect the whole web has been argued about for many years.

Intimately connected with shrinkage is a second characteristic of paper that requires explanation: this is its dimensional instability in the presence of alteration in humidity (moisture expansivity) and when wetted (hygro-expansivity). Any theory of shrinkage on the paper machine itself must be able to explain these dimensional changes and account for the varying degrees of irreversibility which are known to occur when paper is dampened and re-dried.

To consider first the nature of shrinkage itself, in recent years the theories of Page and Tydeman and their colleagues at the British Paper and Board Research Association have become generally accepted as giving, in broad outline, an adequate explanation of this phenomenon. The more important results reported by these workers (see particularly references 80 and 128) will now be briefly described.

During drying, individual fibres may shrink as much as 20 per cent to 30 per cent. in the transverse direction, but only 1 per cent. to 2 per cent. longitudinally. This difference in shrinkage, related to the preferential orientation of fibres in the machine direction, has for a long time been regarded as responsible in some way for the common observation that paper made on a Fourdrinier machine always exhibits greater shrinkage in the cross direction than the machine direction.

However, Page and Tydeman have pointed out that a straightforward relationship between individual fibre shrinkage and contraction of the whole web is not compatible with the conventional idea of paper consisting of fibres bonded together at their cross-over points; such an assemblage of fibres would contract only by an amount equivalent to the longitudinal shrinkage of individual fibres and would in fact be independent of any transverse shrinkage of the fibres. Figure 5.8 makes the reason for this clear by illustrating that, in the absence of longitudinal shrinkage and with the fibres restricted only at the cross-over points, transverse shrinkage is possible without the overall area of the paper being affected.

This anomaly implies that during shrinkage either a relative sliding movement occurs at the cross-over points, or that the longitudinal shrinkage of fibres is actually greater in the sheet than when measured on individual fibres in isolation, possibly due to a form of enforced miniature crêping along the fibre length. By dyeing a few fibres in a handsheet and comparing microscope photographs covering the same field before and after drying the sheet with complete freedom to shrink (by floating in a
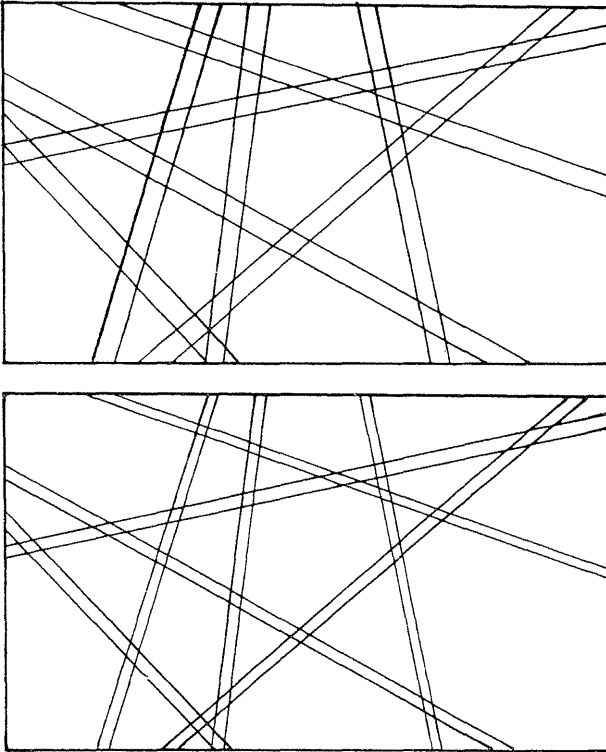
Fig. 5.8. Diagram to illustrate that transverse shrinkage of fibres does not produce sheet shrinkage if only the centres of the bonded crossings are fixed (after Page and Tydeman)

mercury bath), Page and Tydeman found that individual fibres did in fact shrink in length to a much greater extent than had hitherto been measured on isolated fibres not forming part of a sheet. By increasing the beating degree of the fibres comprising the handsheet, fibre shrinkages as high as 12 per cent. were obtained; furthermore, it was shown that the contraction of the whole sheet was always the same as the average longitudinal shrinkage of the fibres. Careful examination of the positions of the individual

dyed fibres showed no relative movement at the points where they crossed other fibres.

The relatively large longitudinal shrinkages observed in this work appear at first sight to confirm that some form of micro-crêping of individual fibres between bonds must occur during drying. But there is no reason why such micro-crêping should not be observable when isolated fibres are dried, and also the largest sheet shrinkages occur in papers that are highly beaten and therefore have a lower portion of their length free from contact with other fibres. It is apparent, therefore, that the shrinkage of a fibre is promoted not between bonds in the unattached portions of the fibre, but at the bond sites themselves. To account for this it must be assumed that fibre-to-fibre bonding is strong enough during shrinkage for the transverse shrinkage of one fibre at a crossing to produce a compressional force causing a contraction in length of the other. Although the unbonded areas of the fibre shrink in length only by a very small degree, at the bond sites the high transverse shrinkage of other fibres in contact induces a much greater total reduction in length. This in turn is transmitted to the sheet as a whole and results in an overall shrinkage of the same order. The greater the degree of beating with corresponding production of bonds between fibres, the greater the bonded length of individual fibres and the greater the overall shrinkage.

This explanation of the nature of shrinkage in the web has been confirmed by Page and Tydeman in a number of different experiments in which, amongst other results, longitudinal shortening from micro-compression in fibres at bond sites has actually been observed and photographed. Apart from contraction at the bond sites, kinks (especially in longer, unbeaten fibres) and micro-crêping can also be observed in the unbonded portions of the fibres; this is a direct result of the compressional forces which must be set up between the fixed bond sites in individual fibres if the sheet is to shrink and at the same time retain its general shape and structure. Thus, the total longitudinal shrinkage of individual fibres in the sheet is compounded of the shrinkage at the bond sites themselves, together with a certain amount of enforced compression in the free areas. It may therefore be expected that the magnitude of shrinkage in a sheet of paper depends primarily on three factors: the intrinsic potential shrinkage of the fibres primarily in the transverse direction; the extent of bonding which occurs in the sheet; and the resistance of fibres to micro-crêping and to bending and kinking in the free regions of fibres, i.e. the general rigidity of the fibres towards compressional forces acting along their axes. Where orientation occurs in the sheet, the transverse shrinkage of fibres in the preferred direction acts to a greater proportional extent on fibres aligned at right angles, hence more contraction of the sheet will also occur at right angles to the preferred direction.

5A.3 2 Expansion of paper on re-wetting

In the presence of a higher humidity, or when immersed in water, a dimensional expansion takes place in a sheet of paper. The relationship between this expansion and the shrinkage which occurs during drying is of

both fundamental and practical interest, and much investigational work has been done on this subject. Page and Tydeman, in their experiment using dyed fibres in handsheets dried without restriction to shrinkage, found that re-wetting of the paper produced a longitudinal expansion of individual fibres which was the same as that of the sheet as a whole. This confirmed that changes in sheet dimensions depend essentially on the changes in length actually taking place in individual fibres in the sheet.

Expansion of a sheet on immersion in water is not completely reversible; normally only about 40 per cent. to 70 per cent. of the shrinkage is recovered, and reversibility tends to diminish when fibres are more highly beaten. This can be attributed basically to incomplete recovery in length of individual fibres due to physical changes produced by the kinking and micro-crêping. It is probable too that the original transverse shrinkage of the fibres may not be completely reversible and also surface tension contractions associated with the earlier stages of drying may result in irreversible changes in position relative to contiguous fibres within the framework of linkages set up by the bonds.

Dimensional changes in the presence of a higher humidity have a similar effect, though of a lower magnitude.

5A.3 3 Effect of restricting shrinkage

On a paper machine the web is always subjected during drying to forces which modify the amount of shrinkage that can take place: obvious examples are the draw, which affects machine-direction shrinkage, and the felt tension, which affects both machine- and cross-direction shrinkage. S. F. Smith (2) was the first to recognize the importance of these restraining forces and to investigate the effect of what he termed the 'dried-in strain', the difference between the percentage shrinkage that would occur without restraint and the percentage shrinkage in the same direction that actually does take place on the machine. He measured first the percentage shrinkage in the cross direction which occurred up to various positions in the drying section of an M.G. board machine with pre-dryers and after dryers, and compared this with the shrinkage that took place when samples taken before the drying section were allowed to dry to the same moisture content but with freedom to shrink; the extent to which shrinkage in the cross direction had been prevented (or 'dried-in strain' developed) was thus determined. Samples drawn from the same positions in the section were then immersed in water and re-dried without restraint, the change in length caused by doing this being measured. In every case wetting and re-drying caused the initial cross-direction dimensions to shrink by an amount which corresponded (but with lower magnitude) to the 'dried-in strain' that had been induced up to that position in the dryers.

The importance of this work lay in the recognition that the restraint conditions of drying affect the final condition of paper and that the process is partially reversible by wetting out and re-drying the paper under different conditions of tension. Other workers have since shown that restraint in drying also affects the moisture and hygroexpansivity of the paper: in general the less shrinkage is allowed to occur during drying, the lower are

the dimensional changes of the paper when afterwards immersed in water or placed in a higher humidity.

These phenomena are readily explicable by Page and Tydeman's theory. Restraint during drying will hold individual fibres in tension and prevent the development of kinks in the free area of the fibres and of micro-crêping at the bond sites. This will cause the longitudinal shrinkage of individual fibres, and hence of the sheet as a whole, to be less than would occur under conditions of complete freedom. If the sheet is allowed to pick up moisture or is immersed in water, the length of fibres will increase but the magnitude of the increase must be smaller because there is less length to recover. The greater the restraint during drying, the more this will apply. However, once the sheet is re-wetted, apart from physical changes induced in the fibres which prevent complete recovery of their original length, the general sheet conditions are returned to their previous state. Drying without restraint will then result in similar behaviour to that of a sheet dried free to shrink which has not first been dried under restraint. If a sheet dried under restraint is put through a number of humidity or wetting cycles involving pick-up and loss of moisture with freedom to shrink, a further, but gradually diminishing, amount of the shrinkage lost by the initial drying restraint is commonly recovered at each cycle. Thus, some of the physical changes induced by restraint during drying must also be reversible given suitable conditions.

5A.3 4 The effect of drying restraints on strength properties

Restraint during drying affects the strength properties of paper as well as the dimensional stability. Most of the work on this subject has been done in the laboratory and a useful summary of this, together with a report of some recent detailed work of their own, is given by Gates and Kenworthy (85). The only detailed report on the practical effects of changing restraint conditions on an actual paper machine is described in the next section.

If tension is applied in any particular direction during drying, and shrinkage in that direction thereby restrained, then it appears that the tensile properties of the paper in the same direction are also affected in such a way that the extensibility is reduced. In general, the less the shrinkage that is allowed to occur, the lower the stretch of the paper and the total energy required to bring about rupture, but the greater the tensile strength.

According to Gates and Kenworthy the relationship between shrinkage on the one hand and stretch and tensile strength at rupture on the other is approximately linear; as regards stretch the relationship applies irrespective of the degree of fibre orientation in the sheet (which governs the relative magnitude of directional tensile properties in the first place), though the relationship between shrinkage and tensile strength is more prominent as orientation increases. Anisotropy of stretch may thus be attributed mainly to differences in drying restraints (primarily because of the close association between stretch and the shrinkage that has occurred in drying), though if the sheet has a high degree of fibre orientation, some anisotropy would still exist even though tension during drying were even in

both directions. By contrast, anisotropy of tensile strength, though also dependent on differences in the drying restraint applied, is mainly controlled by the fibre orientation. The following table of ratios between results in the machine and cross directions quoted by Gates and Kenworthy illustrates this:

	Draw	**Degree of anisotropy**	
		Tensile strength	Extension to rupture
Random Orientation	None	1·09	1·27
	High	1·15	2·58
High Orientation	None	2·05	1·89
	High	2·34	2·99

These results emphasize the difficulties of making a sheet of paper that is free from directional properties with regard to strength. As long as fibre orientation exists, it is hardly possible to obtain tensile isotropy, though by using very slack draws together with devices for restricting shrinkage in the cross direction it appears possible that isotropy of stretch properties may be obtainable.

A general explanation of these phenomena has been presented by Page and Tydeman. In the first place, they consider that under the gradually increasing load of the tensile test the kinks and the micro-compressions at bond sites of individual fibres are gradually pulled out until a point is reached where little further stretch is possible; greater load then comes to bear on the bond sites themselves until the shear strength of the bonds is exceeded and slippage follows with final rupture at the weakest spot. Thus, the strong correlation between the shrinkage occurring during drying and extensibility of the paper is accounted for by the fact that greater shrinkage implies a higher proportion of kinking and micro-crêping in the fibres which are therefore able to stretch more. When shrinkage is inhibited, this is at the expense of a weakening of bond strength; hence the energy required to rupture paper is lower when less shrinkage has occurred during drying.

If dry paper is subjected to tension and then released, above a certain tension a permanent extension or 'set' is found to have taken place. This may be attributed to disruption of micro-compressed regions at bond sites and of kinks that have been straightened out under the tension and do not return to the same position. Over a long period some recovery of the lost shrinkage occurs, i.e. the permanent set gradually diminishes, and also according to Rance (4) 40 per cent. or so of the permanent set can be removed by wetting and drying; these are further indications that physical changes induced by tension in the sheet are partially reversible under suitable conditions. In the draw at the calenders tension is applied in the machine direction to paper which is dry, hence on release from the web some permanent set may be expected to be already an inherent part of the paper and this may well modify the dimensional stability and strength characteristics. Rance argues from this that apart from shrinkage restraint during drying, draw at the calenders must also affect the final properties of the paper, though no direct confirmatory work has in fact been reported on this.

5A.3 5 Drying restraints on a paper machine

Arlov and Ivarsson (3) have reported some interesting results obtained by varying the draws and felt tension of the Swedish Central Laboratory experimental machine, and it is proposed now to describe these in some detail and discuss their significance. In this work for each condition of draw and felt tension the dryness of the web from cylinder to cylinder was measured, together with dimensional changes in the machine and cross directions. All the work was undertaken with constant wet-end conditions and a machine speed between 160 and 220 f.p.m. Dimensional changes were measured using a special device consisting of two cogged wheels set at a fixed distance apart; these could be used to mark the web at any point in the dryers, and the distance at the reel-up between the lines formed by the two wheels, and between adjacent cogs on each wheel, then gave the shrinkage that had occurred from that point in the dryers in the cross and machine direction, respectively.

It was found in the first place that changing the draw and felt tension had little effect on the drying curve due, it was presumed, to the good ventilation on this particular machine. Normally it would be expected that slack felt tension would reduce heat transfer, necessitating a higher steam pressure and a different drying rate. The drying curve common to all the tests is shown in Fig. 5.9, together with the dimensional changes measured down the machine in machine and cross directions.

These results show that a relatively high tension in the sheet, i.e. tight draws, not only decreases shrinkage in the machine direction, but also causes increased shrinkage in the cross direction (this has also been found in several laboratory experiments). Tight felts reduce cross direction shrinkage but appear to have an opposite effect on the machine direction. Shrinkage of the sheet is small down to a moisture content of about 40 per cent., and up to this position in the dryers extension of the sheet in the machine direction is possible by tighter draws; this produces a corresponding contraction of the sheet in the cross direction, which is also seen to be particularly influenced by the draw in this region. Below 40 per cent. down to about 15 per cent. moisture content, shrinkage of the sheet increases sharply and in this region, although the influence is still present, different draws and felt tensions have a decreasing effect possibly because the forces of contraction against which they must act become relatively great. General confirmation of this has come from laboratory simulation experiments reported by Kenworthy (103), who found that the influence of tension in drying is rapidly reduced as moisture content decreases from about 55 per cent. down to 30 per cent. or so.

Many other workers have found in laboratory experiments that the shrinkage rate increases below 30 per cent. to 50 per cent. moisture content. It has also been reported that greater beating of the paper furnish, apart from increasing the rate of shrinkage throughout the drying section, causes the shrinkage rate to start increasing when the web is damper though the transition is then less sharp between the two rates of shrinkage. A more highly beaten paper shrinks more in the early part of the drying section presumably because surface tension forces act on a more closely

connected assemblage of fibres which are, in turn, more flexible and yielding.

The change in shrinkage rate appears to take place at about the position in the dryers where the rate of drying begins to fall off (in Fig. 5.9 this is at the inflexion point of the drying curve, i.e. about 40 per cent. moisture
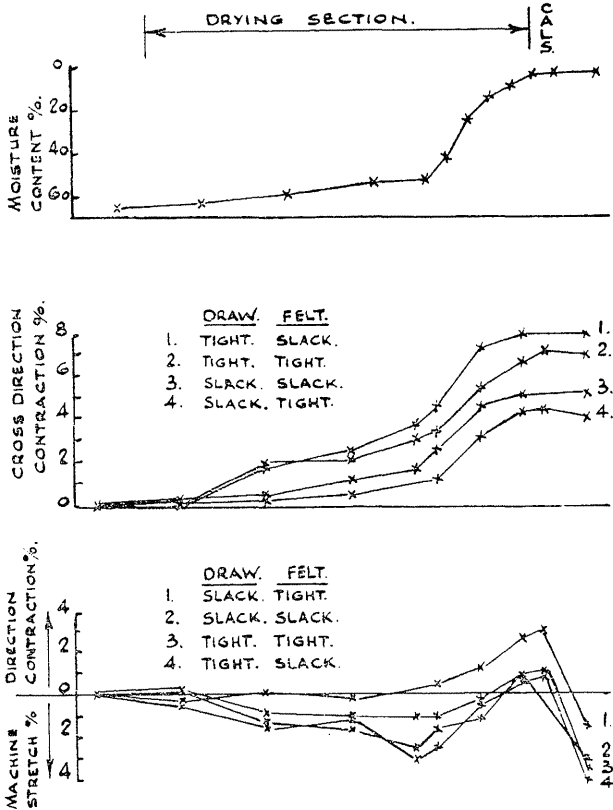
Fig. 5.9. Change in moisture content and dimensional changes in the cross and machine directions of a web passing along the drying section under different conditions (after Arlov and Ivarsson)

content). It is reasonable to suppose that the change is closely associated with completion of the removal of 'free' water from the web and the commencement of evaporation of water within the fibres themselves. The basic cause of shrinkage thus changes at this point from the relatively small contractive forces produced by surface tension to the much more substantial forces resulting from the reduction in length of individual fibres.

It will be noted particularly that a large decrease in machine-direction shrinkage occurs at the calenders, to such an extent that in every case the

overall dimensional change in this direction amounts to a stretch rather than a contraction in the sheet length. This bears out Rance's contention that the magnitude of the calender draw can be very important in deciding the final properties of the paper.

The effect of drying on the mechanical properties of the paper was also investigated by Arlov and Ivarsson under conditions when the drying rate on the machine was adjusted to be as linear as possible all the way down the section; samples were extracted at various positions down the dryers
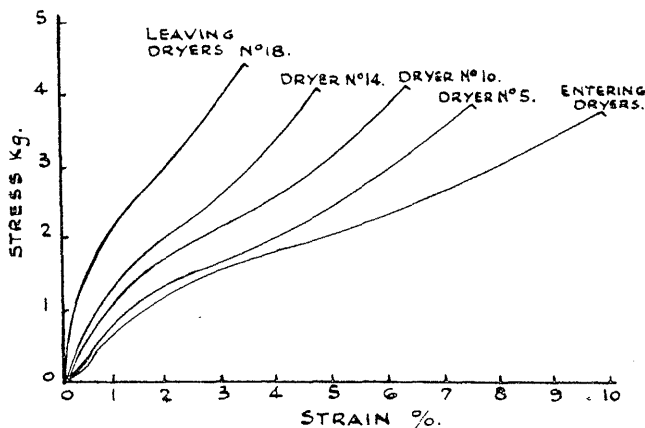
Fig. 5.10. Machine direction stress–strain curves of paper extracted from different parts of the drying section (after Arlov and Ivarsson)

and were then allowed to complete their drying with freedom to shrink. Figure 5.10 shows the change produced in machine direction stress–strain curves obtained with a special tensile tester; the results bear out the observations that the progressive effect of tension in the sheet during drying is to reduce shrinkage and subsequent stretch, but increase the tensile strength required to break the paper.

5A.3 6 Controlling shrinkage on the machine

For many types of paper it is important to be able to obtain some desired degree of dimensional stability, strength isotropy, or other special properties such as maximum extensibility in one or other direction. The rôle of fibre orientation in the sheet has an important bearing in such cases, for example it has already been seen that tensile strength isotropy is largely dependent on the degree of fibre orientation, but in the present context it is proposed to discuss only the influence of drying. In particular, it is most useful to be able to control separately the shrinkage taking place in machine and cross directions in the dryers.

Taking first machine-direction shrinkage, the results obtained by Arlov and Ivarsson indicate that this can be regulated to some extent by the felt tension, but the most important and controllable influence is the sheet

tension in the draws. Increasing the sheet tension on a machine within the practical limits demanded by smooth running may be expected to produce a decreased extensibility and less dimensional instability in the machine direction, though it also appears to induce the opposite effect in cross-direction properties. This applies particularly to the early part of the drying section although often there is only one position at this stage where a draw can be applied so the scope for manipulation is limited. When the expense is justified, greater flexibility could no doubt be obtained by dividing up the early cylinders into a number of individual drives each, of course, with its own pair of dry felts.

Shrinkage is also affected on some machines by the practice of gradually reducing the diameter of the last few cylinders in an endeavour to maintain as near as possible the same tension in the sheet in the region where most of the shrinkage takes place. But this is obviously a permanent arrangement and is only suitable where there are no substantial differences in the shrinkage pattern, such as occur between different grades of paper and under different beating conditions, for papers produced on the machine in question.

Shrinkage in the cross direction, which may be as little as 2 per cent. but with heavy, well-beaten papers can amount to 9 or 10 per cent., is less easy to regulate on most machines; but it is particularly important to keep a check on this, if only to prevent shrinkage becoming excessive and affecting production by narrowing too much the deckle at the reel-up. It has been seen that tight felts help to reduce cross-direction shrinkage; also slackening the machine-direction sheet tension, though possibly not restricting shrinkage in the cross direction, will prevent its increase at the expense of tight draws. But the use of felt tension to regulate cross-machine shrinkage of the paper carries with it the objection that the drying conditions with respect to heat transfer and steam consumption may thereby be affected, and anyway on many machines it is not practicable from the point of view of running the felt to alter the tension to any significant degree.

A device known as the 'textile stenter' has been adapted to grip the edge of the paper web and restrict excessive web shrinkage when the web is unsupported in a free draw, and details have also been given of equipment consisting of a rubber belt which is pneumatically pressed and drawn across the paper as it passes over a drying cylinder, thereby spreading the web across the machine as it follows the belt (120). But in recent years a more flexible method of regulating cross-direction shrinkage has appeared, the expander roll with fixed or variable bow. Gallahue (73) and Fahey and Chilson (84) have given details of the use of this device, and claim that shrinkage in the cross direction is reduced and also (as would be expected) there is an improvement in cross-direction tensile strength and dimensional stability. Expander rolls have been used in several positions and appear most effective in the early part of the drying section (where, it may be noted, draw has also been found more effective for altering machine direction shrinkage). No 'noticeable' effect on machine-direction shrinkage is reported, nor any 'appreciable' effect on tensile strength in the machine direction.

It is also possible with expander rolls to bring shrinkage at the edge of the sheet under better control by adjusting relative web tension. This is of particular importance because shrinkage of the paper up to a few inches from either edge is generally affected by differences in tension during drying (due to the greater freedom to shrink cross-wise, to differences in substance, and to differences in drying rate which affect the eventual shrinkage, as discussed below); in extreme cases very prominent differences in the dimensional stability and strength characteristics of the web at the edges can occur.

5A.3 7 Cockling

Cockling of paper when cut into sheet form, and certain forms of distortion in reel form, are also due basically to differences in tension set up during drying whenever the drying rate is different in one portion of the web to adjacent positions. Suppose, for example, that drying is slower for some reason in one region of the web. The surrounding area, because it dries quicker, will begin to shrink earlier and will consequently exert a tension on the damper region. This will cause the damper region to dry with a lower amount of shrinkage and when the web is finally dried to the same moisture content this region has become stretched to a slightly greater area.

Distortions of the machine reel often emanate from differential shrinkage and this may originate in cross-machine substance variations: a persistent narrow heavy streak will produce a wrinkle running round the reel the prominence of which will depend on the winding tension. Normally though, the causes of reel distortions are complicated by associated moisture and calendering differences, a topic discussed further in 5C.5 4 and elsewhere.

When cut into sheets, a region of the paper which has been stretched will exhibit itself as a bulge; the bulge may at first be hardly noticeable, particularly if the sheet comes from a tightly wound reel, but once the paper relaxes in sheet form the familiar appearance of cockling becomes more apparent. It is in this form that distortions due to differences in tension set up during drying are most commonly encountered. In certain cases, as the sheet rapidly picks up moisture from the atmosphere the lower moisture expansivity of the stretched area of the sheet may gradually reduce the prominence of the cockle.

Cockling produced by cross-machine substance unevenness shows up very prominently in sheets stacked off the cutter and in this respect, as in the case of similar faults in a reel, the slightly heavier substance of the stretched portion is generally associated with slightly greater thickness which therefore accentuates the trouble. Differences in moisture content across the web entering the dryers, caused for example by a ridge in the wire or a plugged wet felt, can produce this same effect when they are severe and confined to a relatively narrow width. Likewise differences in tension of the dry felt as a result of being stretched on some occasion and very bad unevenness in cylinder surfaces produced by a build-up of scale and dirt can both have a similar effect on the paper. A poor breast box and

slice can deposit relatively large areas of stock which are over- or under-weight and this also can produce cockling, though in a less systematic manner.

5A.3 8 Curl; the fundamental mechanism

The subject of curl, in so far as it is associated with two-sidedness and fibre orientation during formation on the wire, has already been considered in some detail. In this section the added complexities of the influence of drying on curl are dealt with. An understanding of how the conditions of drying come to affect curl in the finished paper has gradually emerged over the years as a development from observations of the effect of drying restraints on paper, as described in the previous section. The foremost workers in this field, from whose reports the following is derived, are Brecht *et al.* (14, 21, 42, 70), Glynn *et al.* (52, 74), and Newman *et al.* (28, 86).

The development of curl in a sheet of paper depends in the first instance on differences in the unstressed dimensions of the two surfaces. For instance, if the top side would take up when completely relaxed a larger area than the wire side, then the sheet will tend to curl towards the wire side. The axis of curl depends primarily on the relative difference in relaxed length of the two sides in the machine and cross direction; the magnitude of curl depends on the relation between the extent of these differences and the rigidity of the sheet, i.e. on the balance between the stress towards bending set up by the differences in dimension of the two sides of the sheet related to the resistance to bending inherent in the structure of the sheet. Both axis and magnitude of curl thus depend on an interaction of stresses in the sheet; a 20 in. × 30 in. sheet may curl in one direction while two 20 in. × 15 in. sheets cut from it may curl in the opposite direction.

This fundamental conception of the mechanism of curl has been directly demonstrated by Glynn and Gallay (74). In this work a laminated paper prepared by couching together two standard handsheets was subjected to non-uniform drying on the two surfaces and the curl developed was measured. The two sections were then separated and their equilibrium lengths measured: a close correlation was shown to exist between the differences in unstressed length of the two sides and the magnitude of curl.

Other work which illustrates the dependence of curl on differences in the unstressed dimension of the two sides is reported by Brecht *et al.* (42). In these experiments one surface of a sheet of paper was insulated from the other by a specially devised container, and the relative moisture contents (and, hence, the natural dimensions) of the two surfaces were then altered either by blowing dry air on one side or maintaining the air in contact with two surfaces at different relative humidites. Whenever the difference (and hence unstressed area) between the equilibrium moisture content of the two sides was increased, e.g. by increasing the difference in relative humidity between the two sides, then the curl observed was greater. The rate at which the sheet curled also appeared to depend primarily on the magnitude of the moisture gradient that was set up through the sheet: increasing the

velocity with which dry air was blown onto the sheet, or the difference in humidity between the two sides, increased the rate of development of curl. Also, thin paper curled faster than thick paper in comparable conditions, presumably due to the lower resistance to bending, although the final degree of curl once equilibrium was established was little different in the two cases (this may be attributed to the lower difference for the thin sheet in final moisture content of the two sides, associated with the lower rigidity). Sheets made from beaten pulps always gave a greater degree of curl in comparable conditions, a result that is expected due to the overall higher moisture expansivity.

5A.3 9 Curl; the effect of changes in atmospheric conditions

These experiments illustrate the basic mechanism of curl and the inter-action of forces that comes into play. Under normal conditions, of course, both sides of a sheet of paper are subjected to the same atmospheric conditions, but even so changes in humidity will affect the degree of curl. For this to happen it is only necessary for the moisture expansivity of one side of the sheet to differ from the other, as is the case whenever there is appropriate two-sidedness in the constituents of the sheet. Change in curl then takes place towards the side having lower moisture expansivity when the humidity is increased, and away from that side when humidity is decreased. A perfectly homogeneous sheet does not curl in the presence of humidity changes; Brecht illustrated this by gluing strips of paper together to form a sheet having two identical surfaces.

From this it follows that anything which affects the relative moisture expansivity of the two sides of a sheet will alter the behaviour of the paper under a change of atmospheric conditions. The axis of the curl, though mainly determined by the relative degrees of fibre orientation in the two principal directions, will also be affected by the restraint imposed on drying. If shrinkage is prevented in one direction during drying, this will reduce the moisture expansivity in that direction and thereby create a tendency for curl also to take place in the same direction because the greater expansivity is at right angles. Such an effect would be independent of fibre orientation, though of course any orientation in the sheet would affect the relative degree of expansivity in the first place.

To summarize, although a sheet of paper may lie flat in one particular atmosphere, curl can occur if the sheet is placed in a more moist or dry atmosphere due essentially to differences in moisture expansivity of the two sides of the sheet. The magnitude of the curl depends on the internal stress caused by the differences in expansivity in relation to the rigidity of the sheet; the axis of curl depends on the relative differences in expansivity in the two principal directions which in turn are governed by fibre orienta-tion and the restraints exerted in drying. To this extent, it may be noted, altering draws and felt tension can affect curl by changing the potential expansivity in one or other direction. In practice, however, it is not easy to decide how to alter curl by this means because the effect depends not on the magnitude of shrinkage occurring in any particular direction, but on

the difference in expansivity on the two sides of the sheet in the one direction compared to the other.

5A.3 10   Curl; direct changes induced in drying

Attention has so far been focused on the curl which may be induced by atmospheric changes. It will be readily appreciated that the same factors are responsible for any inherent curl of the paper as produced on the machine and in practice it is usually this source of curl which is the more prominent in Fourdrinier papers. By 'inherent curl' is meant simply the curl that a sheet of the paper would assume immediately it were released from the web but before any change occurred in the moisture content. Although in practice it is not easy to distinguish between such inherent curl and the curl induced by changes in moisture content of the sheet as it reaches equilibrium in the atmosphere, it is important nonetheless to be clear that there are two sources.

Inherent curl is a product of the internal stresses set up through the thickness of the sheet due to differences between the two sides in shrinkage potential during drying. For example, if by virtue of its composition the top side of the sheet has a natural overall shrinkage during drying which is greater than the wire side, then the top side of the sheet will try to assume a smaller area. The structure of the sheet will prevent this actually occurring and instead a degree of stress is set up within the sheet in which the top side is restrained from shrinking and is in tension while the wire side undergoes a certain amount of compression. On release from the web these stresses relax to create, in this case, a curling tendency towards the top side.

It is possible during the drying process to alter the stresses set up through the thickness of the sheet and, thereby, the inherent curl in the paper. Glynn *et al.* (52) have reported several interesting experiments which demonstrate this. Firstly, sheets dried free to shrink under an infra-ray lamp always curled away from the heat source irrespective of whether the top or wire side faced the heat. When dried with one side in contact with a metal plate, the sheet curled towards the contact surface irrespective of which side heat was applied to, i.e. through the plate or on the free surface of the sheet. Finally, with handsheets dried on a curved dryer and the sheet in contact in various combinations with the cylinder, a felt or wire screen, or sandwiched between felts and/or screen, the direction of curl was shown always to be towards the side from which moisture was removed last. The same occurred with various types of machine-made paper which were re-wetted and then dried under similar conditions. The hotter the surface of the curved dryer, the greater the curl induced; increased beating increased the curl but size, alum and loading had little effect.

These results are explicable only in terms of the internal stresses set up in the sheet during drying. In all cases the curl is towards the surface which dries last: the side away from the heat source in the first experiment, the side facing the metal surface (which would prevent moisture removal from that side) in the second experiment. The side drying first will tend to

shrink earlier and will therefore be continually subjected to more restraint than the opposite side; only when drying of the first side is completed and shrinkage ceases is the opposite side prevented from shrinkage any more and an increasing restraint put upon it. With drying completed the side of the sheet dried first will have tended to shrink less, i.e. have a greater natural area, than the opposite side from which moisture is removed last, so that the sheet will be subjected to a stress which on relaxation will produce a curl away from the side dried first. The greater the tendency for one side to shrink earlier than the other, by quicker drying or by the sheet having greater potential shrinkage, the stronger is the curl induced by this means. In any particular case, the magnitude of curl will depend on the moisture difference set up during drying between the two sides of the sheet in relation to the thickness, i.e. to the moisture gradient through the sheet.

5A.3 11 Correction of curl
It is evident from this explanation that a means is available for correcting curl induced by the two-sided structure of the paper. To return to the example of the sheet which by virtue of its composition has a greater shrinkage potential on the top side, it was shown that under unrestrained drying this would tend to curl towards the top side. If now drying is performed in such a way that the top side is dried quicker than the wire side, a counteracting curling force will be produced. The tendency for the top side to assume a smaller area by virtue of its desire to shrink more is counteracted by removing moisture earlier from the top side and thereby subjecting it to greater restraint during drying and increasing the natural area.

This effect has been demonstrated on a paper machine by both Brecht *et al.* (42) and Hendry and Newman (86). However, difficulties arise in its use as a means of correction because of a difference in behaviour in the two principal directions. Suitable correction by differential drying of a greater potential shrinkage on one side of the paper in the machine direction is unlikely to be exactly suitable for correcting the same difference in the cross direction.

Hendry and Newman describe running a machine with the top cylinders hotter (200 deg. F. as against 145 deg. F.) than the bottom, then vice versa. Curl in strips cut with axis parallel to the machine direction (a measure of curl with axis in the cross direction) was unaltered, while curl in cross-direction strips altered considerably in such a way that the curl was always away from the side contacting the hotter cylinders, i.e. the side dried earlier.

For all the knowledge of the sources and behaviour of curl that is now available, it will be evident from the sheer complexity of the situation that a solution to any individual curl problem presents considerable difficulties. A thorough analysis of the causes of curl in one particular paper on a machine can be extremely time-consuming and it is difficult to obtain consistent results. Certainly differential top and bottom drying in the last bank of cylinders provides an invaluable aid to the machine crew provided

a systematic and standardized procedure is laid down for assessing the effects of changing the differential in terms of the resulting change in curl. A sweat roll can also have some effect on curl because moisture is added to one side of the sheet before calendering, but this is not so controllable. In practice differential drying together with careful manipulation of draws and felt tension can enable curling tendencies to be kept under control, but considerable care and experience is required.

5A.3 12 Alteration of paper properties with atmospheric changes

To complete this section, brief mention will now be made of the effect that changes in atmospheric conditions have on the properties of paper. The moisture content after conditioning in the standard atmosphere of 65 per cent. relative humidity and 68 deg. F. varies considerably from one type of paper to the next, being as low as 5 per cent. for bible tissue and over 10 per cent. for mechanical printing. According to Brecht (41) the equilibrium moisture content depends on the hemicellulose and lignin content of the paper, the presence of filler (which decreases the moisture content as its proportion is increased), but not so much on beating.

The moisture content of paper in any atmospheric condition is closely dependent on the relative humidity and actually depends on whether equilibrium is approached from a higher or lower initial moisture content. Fig. 5.11 is a typical curve illustrating the behaviour of moisture content as relative humidity is varied; much detailed work on this subject dealing with a whole range of papers has been published by Crook and Bennett (71). The time required to achieve final equilibrium can be long, a matter of many hours, though blowing air on the paper hastens this appreciably. However, when paper is first exposed to the atmosphere on extraction from a reel the initial rate of change is rapid; newsprint taken off the reel at 6 per cent. moisture content picks up a further 1 per cent. in under a minute. More will be said about this, and the problems it presents with regard to testing the moisture content of paper in a reel, in later sections.

Various properties of paper are closely affected by the moisture content. Fold, stretch, tear, and thickness increase in value at higher moisture contents, while tensile strength, air resistance, and stiffness decrease; burst shows a maximum and begins to drop off sharply above 6 to 7 per cent. moisture content. Fold is most affected by changes in moisture content, followed by stretch, tear, stiffness, tensile strength, burst, air resistance, and thickness. Comprehensive data on this subject can be found in the same report by Crook and Bennett.

Other results have been reported by Brecht (41) who found that smoothness decreases with increasing moisture pick-up. This work will be referred to in greater detail when discussing the effects of calendering. A further observation by this author is that static electric charge drops rapidly on a damp reel that is placed in dry air, but a dry reel in damp air keeps its charge indefinitely. Thus, the higher the moisture content of the paper the less static it is likely to carry. Brecht also states that less dust is present in a reel when moisture content is higher.

Temperature, irrespective of humidity differences, has only a small effect

on the properties of paper and is hardly significant in relation to the normal changes in indoor temperature which occur in this country, certainly in comparison with ambient humidity changes. Fold is most affected by temperature changes and to a lesser extent strength tests; a
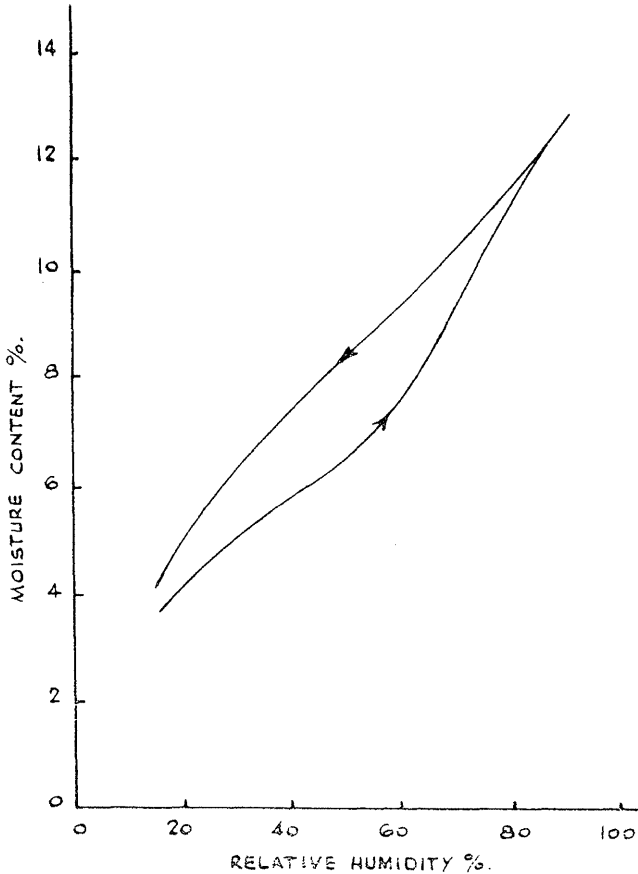
Fig. 5.11. Typical curve showing the change in moisture content of paper caused by increasing and then decreasing relative humidity

15 deg. F. rise in temperature is reported to reduce tensile strength by about 5 per cent. and burst strength by $2\frac{1}{2}$ per cent. The effect of temperature on moisture content, thickness, air resistance, and tear is negligible.

5A.4 CALENDERING

At a really fundamental level relatively little is known of the way in which calendering affects paper. Some consider that damage is done to fibre

411

bonds on the surface of the paper and this reduces the resistance of the outer layers of fibres to vertical stresses such as are applied during printing; fibres are thus more easily lifted up from the surface of the paper or loosened completely from the sheet to create dust and fuzz. The predominant effect of the calenders is on the paper surface and a comparison before and after calendering (such as in the light micrographs on supercalendered paper presented by Emerton (72)) shows up well the change that occurs. Individual fibres which are initially sticking out proud from the surface are seen to be flattened into close contact with the sheet, while local concentrations of fines and filler (mainly on the top side) become merged in the calendered sheet into a smooth highly-glazed area. Photographs of microtome cross-sections taken through paper before and after calendering reveal that a reduction in the inter-fibre void space occurs and that the lumens of mechanical wood fibres collapse (107, 127).

The effect of the calenders is produced by the heavy compressive force to which the paper is subjected, combined with a certain amount of sliding or rubbing action of the calendar rolls on the paper surface. The process appears to some extent to be reversible: Farebrother, in the discussion on the above paper by Emerton, presented photomicrographs of the same area of paper which show that the general appearance of the sheet after calendering (on a laboratory scale) is largely restored to the uncalendered state by soaking in water and re-drying. On the other hand, bulk and smoothness showed appreciable residual effects due to the calendering and these are the properties most affected in the first place, alteration of bulk and smoothness and reduction of variations in thickness across the web being, of course, the principal purposes for which calenders are used.

What follows represents a summary of the present state of knowledge of calendering. It is confined largely to describing the results of investigations into the effect of calendering on the general properties of paper.

5A.4 1 Change in paper characteristics down a calender stack

Experimental work designed to find out how the properties of paper change as it progresses down a stack of calenders have been reported by Howe and Lambert (61), Wultsch (68), Blanchard *et al.* (82), and Mardon *et al.* (106, 126). There are many practical difficulties involved in obtaining suitable samples for testing as the paper emerges from the different nips under normal running conditions, and the most convenient method appears to be to cut a strip at one edge and catch or blow it off at the positions required, working progressively back up the stack. The rest of the sheet runs through the stack while the strip is sampled and to prevent a break it may then be necessary to widen the sheet back to full width very quickly.

In the work reported by Howe and Lambert, sampling from an 18 in. strip passing alone down the calenders was also tried and gave similar results for thickness and smoothness changes to those obtained with the full sheet. It is presumed that the rolls deflected sufficiently to prevent the full weight of the stack falling on the strip and, if this is generally the case, using only a strip could present an alternative means of experimenting,

although the possibility of a variable bias being introduced makes it preferable whenever practicable in studies of this nature to extract samples with the full sheet running in the stack.

It is interesting to remark at this stage that the change in properties down the stack with only the strip running was more pronounced when passing through at a crawl than at full speed. Under crawl conditions it is to be expected that less distortion of the rolls within the nips occurs, and so there is less likelihood of any relative motion between rolls and paper which could contribute a smoothing effect; but the main difference from operation at full-speed is that pressure is exerted on the paper at each nip for a longer time interval. This is one piece of evidence which indicates the importance of a straightforward compressive action in calendering.

Some of the results obtained by Howe and Lambert on a high-speed newsprint stack are given in Fig. 5.12 which illustrates the changes that occurred in thickness, porosity, and smoothness (top and wire side using a modified Bendtsen apparatus—note that lower readings indicate smoother paper, the Bendtsen test strictly speaking measures roughness). The general shape of each of these curves, the declining effect of successive nips on thickness and the almost linear relationship (certainly as regards percentage change at each nip) for smoothness and porosity, has been confirmed by the results of both Blanchard (on five different stacks) and Wultsch (on a machine making printing paper), though with fine papers Mardon found that reduction of thickness in successive nips appeared on a number of machines to be linear; similar changes in paper properties have also been noted in work on supercalenders. Differences between top and wire side smoothness remain unchanged through the stack.

While thickness, smoothness and porosity are the properties most affected by the calender stack, other observations have shown that gloss increases, and compressibility, stretch, and tear all decrease at a fairly uniform rate from nip to nip. Printability as assessed on a proof press increases fairly steadily (from which it appears that a measure of smoothness can be used to give an indication of changes in potential printability).

Blanchard remarked that woodfree papers are much less affected by the calenders than newsprint and considered that furnish has an important effect. This has been generally borne out in the later work of Mardon, with the additional observation that wood-free papers are relatively more affected in later nips than the earlier nips of a stack.

5A.4 2 Changes in smoothness and thickness on removal from the reel

It is unfortunate that few of the reports quoted above give any details of moisture in the paper. Moisture content is important not only for its direct influence on the effect of the calenders (see next section), but because the time elapsing before testing, and the change in moisture content as the paper approaches equilibrium in the atmosphere, both have an appreciable effect on its measured properties, and particularly on thickness and smoothness. There are obvious difficulties in ensuring that samples are tested in the condition they leave the calender, but the apparent absence of specific precautions to minimize variation from these sources detracts
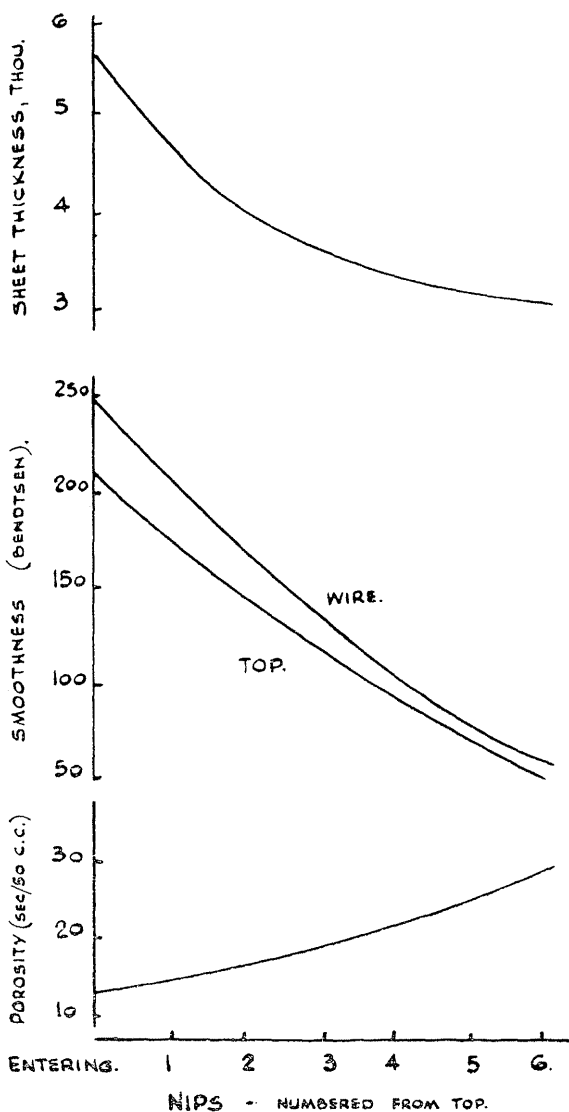
Fig. 5.12. Change in thickness, smoothness and porosity of newsprint passing down a stack of calenders (after Howe and Lambert)

somewhat from the value of the results (there is no mention of protecting samples from the air as much as possible before testing, though Mardon conditioned them for a fixed period to a standard atmosphere which eliminates one source of variation).

Although changes in paper properties after extraction from the reel (especially in moisture content, thickness and smoothness) are well recognized, in fact there is not a great deal of information available showing how rapidly and to what extent such changes take place. The only
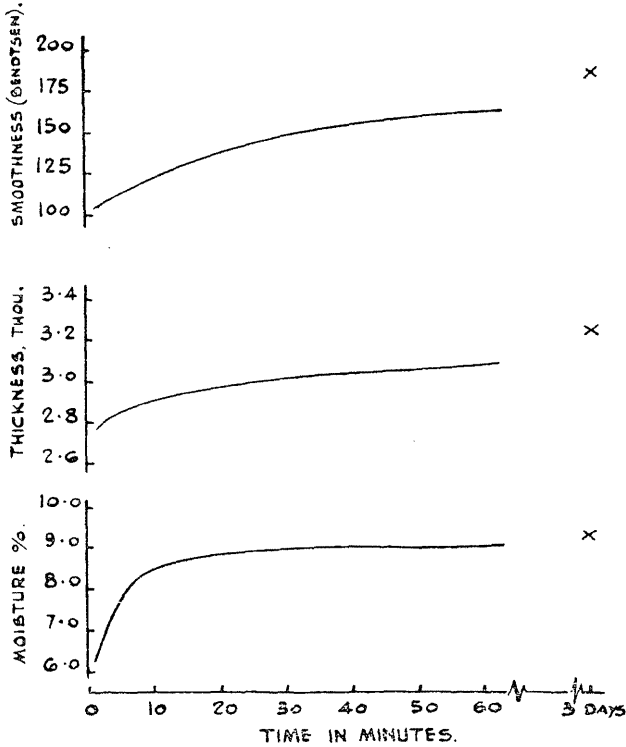
Fig. 5.13. Changes occurring in a sheet of newsprint after extraction from within a reel

really detailed report dealing with the magnitude of change under different conditions is due to Brecht and Heyn (33), but before examining this work it is interesting to consider the manner in which the characteristics of paper can alter in the common case where extraction from the reel brings about an increase in moisture content to equilibrium in atmosphere.

Fig. 5.13 illustrates typical changes occurring in newsprint immediately after it is removed from inside a reel and freely allowed to approach equilibrium in standard atmospheric conditions. Over a period of three days the smoothness decreases from 100 to 185 Bendtsen, and the thickness

increases from 2·75 thou. to 3·25 thou. The moisture curve is also shown and attention is drawn particularly to the rapid change in the first minute.

These curves show that the moisture content of the paper is within 0·5 per cent. moisture of equilibrium after a little over 10 minutes, while after one hour it has virtually stabilized and after three days little further increase has occurred. In contrast both smoothness and thickness show a substantial change between their values after one hour and after three days.

It may be strongly suspected from these results that the initial change in smoothness and thickness on extraction from a reel is due primarily to pick-up of moisture, but that some further alteration continues even after the moisture content has virtually reached equilibrium. This later and more gradual change may be attributed to a gradual visco-elastic relaxation of the sheet from the compressional forces of calendering, a process which can be expected to produce an increase in the thickness and a greater unevenness of the surface as the stresses in individual fibres are relieved and micro-movement occurs.

Though dependent in this way on rheological factors, the magnitude of the change occurring in smoothness and thickness is nevertheless closely associated with the degree of moisture change occurring in the sheet. Brecht and Heyn have obtained substantial experimental data on this by measuring the change after calendering in moisture content and smoothness under a variety of conditions. Their work was done on a laboratory apparatus using two smooth steel discs in a hydraulic press, but 'meticulous studies' indicated that by employing corresponding pressures, the results obtained with this static method are similar both with regard to calendering effect and to change in properties afterwards to those obtained with normal calenders. Three different papers were examined and in each case the effect of calendering at different moisture contents was first determined and then the paper was allowed to condition in three different relative humidities, the change in smoothness and moisture content being measured at appropriate intervals up to 24 hours later.

Considering paper made with a standard newsprint furnish, the following table adapted from the graphs and data available illustrates the changes which occurred in the smoothness values on conditioning to 65 per cent. relative humidity:

Moisture Content per cent.		Smoothness (Bendtsen)	
After calendering	After 24 hrs. conditioning	After calendering	After 24 hrs. conditioning
5·3	10·2	180	350
9·3	10·3	100	160
13·4	11·3	56	76
23·3	11·8	86	185

These figures combined with similar ones obtained when conditioning to 35 per cent. and to 90 per cent. relative humidity (giving a lower and a higher equilibrium moisture content respectively) as well as for the other two types of paper, indicate that the bigger the change in moisture content the greater is the drop in smoothness. This occurs whether a rise takes place in the moisture content (as normally occurs), or whether the paper

416

loses moisture on conditioning, although the overall results show that a much lower proportional drop in smoothness takes place when the moisture content reduces. As an example, paper calendered at 13·4 per cent. and conditioned to 90 per cent. R.H. showed a *rise* in moisture content by 2·1 per cent. and a drop in Bendtsen smoothness from 56 to 120; this may be compared with the drop from 56 Bendtsen to only 76 for a *decrease* of 2·1 per cent. in moisture content, as shown in the table above.

When the moisture content after conditioning closely matches the moisture content after calendering and only a very small change in moisture content occurs then the loss in smoothness is undoubtedly at a minimum. But even in such cases the results of Brecht and Heyn show that an appreciable reduction in smoothness still takes place and this is a further indication of the existence of a visco-elastic relaxation of compressional stresses.

One final point worth mentioning is an observation made by Wultsch (31). This worker reported a large drop in smoothness two hours after normal calendering of a woodfree paper. Even when the same paper received a second moistening and calendering, though this naturally gave greater smoothness off the machine, it did not affect the change in smoothness afterwards, and a similar drop occurred. But if the calender rolls in the second stack were heated, practically no change in smoothness occurred afterwards, although there was at least the same increase in moisture content taking place during the two hour interval.

5A.4 3 Effect of moisture content on calendering

Apart from the dependence of the final smoothness of paper on the change in moisture content taking place after calendering, the initial effect of the calenders is also very closely dependent on the moisture content of the paper. There is unfortunately not a great deal of data to present on this aspect of calendering, despite the fact that the calenders are well known to be sensitive to changes in moisture content.

Laboratory work reported by Jackson and Ekström (104, 123) has confirmed that up to the 12 per cent. moisture region paper is more compressible at higher moisture contents and so would achieve a greater smoothness after calendering. For newsprint, results have been obtained which show that improved surface smoothness, gloss, strength and printability are all achieved by calendering at a higher moisture content. Similar improvements appear when the temperature of the paper web is higher and there are also indications from their work that a temperature of 70 deg. to 75 deg. C. is best for obtaining a high smoothness in calendering; normal operating temperatures of calenders are 10 deg. to 15 deg. C. below this level.

'Blackening' of paper in the calenders, which is due to excessive compression damaging the structure of the paper and creating an optical distortion giving the appearance of greater transparency, is a familiar fault that is caused by having the moisture content too high.

The work of Brecht and Heyn has provided clear evidence of the existence of a moisture content at which calenders have a maximum

smoothing effect. Figure **5**.14 is adapted from their data and the lowest curve illustrates the effect on smoothness of varying the moisture content during calendering; the paper was made from a newsprint furnish and some of the results have already appeared in the table on page 416. A distinct maximum for the initial smoothness immediately after calendering occurs at about 15 per cent. moisture.

The effects of conditioning to 35 per cent., 65 per cent. and 90 per cent. relative humidity are shown in the upper curves which represent the values to which the initial smoothness changes for the three different equilibrium
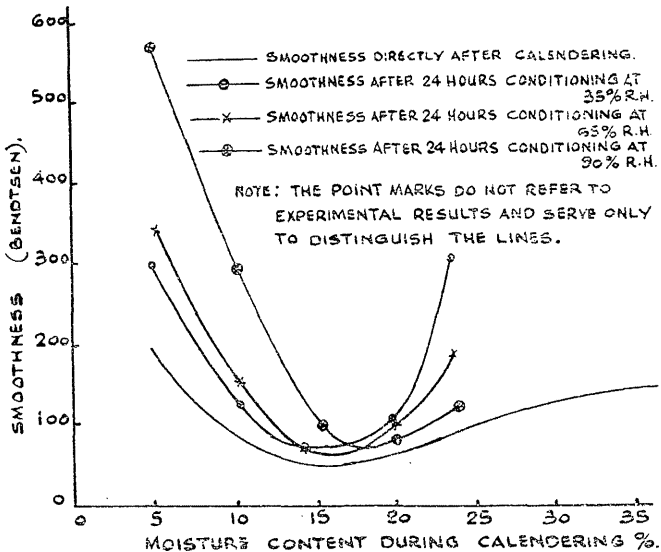
Fig. 5.14. Variation of smoothness directly after calendering at different moisture contents, and the corresponding smoothness after conditioning for 24 hours at three different relative humidities (after Brecht and Heyn)

conditions (the moisture content scale does not apply to these curves). The maximum point is still as evident in each curve but it has shifted position due to the different changes in moisture content occurring before equilibrium is reached in each case: for maximum smoothness in a 35 per cent. humidity atmosphere calendering is best done in this case at about 13 per cent. moisture content, for 65 per cent. humidity at about 15 per cent. moisture, and for 90 per cent. humidity at about 18 per cent. moisture content.

Though the general level of smoothness was different, similar results were obtained for two other types of paper made from 100 per cent. bleached poplar sulphite pulp and 100 per cent. bleached spruce sulphite pulp. Maximum initial smoothness also occurred in each case at about 15 per cent. moisture content, but the maximum smoothness points after

conditioning to the different humidity levels, though following the same sequence, corresponded to a lower initial moisture content in the case of the first pulp and higher in the case of the second.

In the normal course of operation on the vast majority of machines there is no possibility of calendering at moisture contents above 6 or 7 per cent. So the main point of interest in these results from a practical aspect is that higher moisture contents at the calenders can generally be expected to produce a greater smoothing effect. But there is another aspect to this which must be taken into account.

During any particular making the natural variation in smoothness of paper at the reel-up that occurs from one moment to the next due to
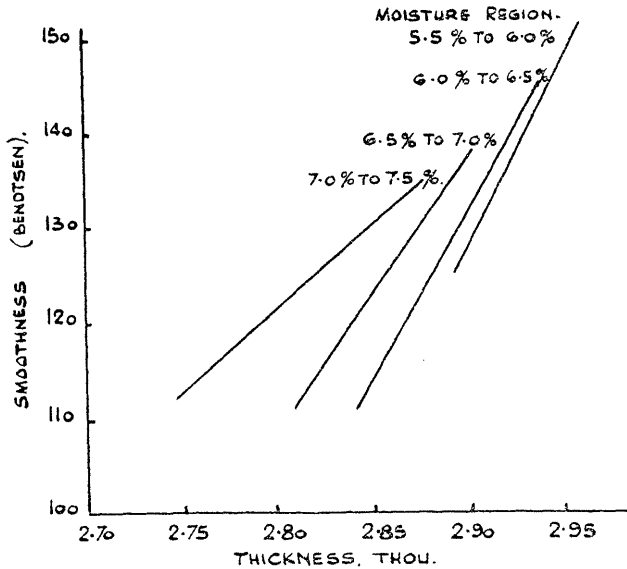
Fig. 5.15. Regression lines showing the dependence of smoothness on the thickness of newsprint reeled at different moisture contents

differences in substance, fibre composition, formation, and so on is closely associated for given calender conditions with the thickness: in other words, when for some reason the smoothness level alters, the thickness will usually also be found to have altered. This association stems from the close relation between the compressive effect on the paper at any time and the resulting smoothness.

The precise relation between smoothness and thickness occurring in calendered paper also appears to depend on the moisture content. This is shown in Fig. 5.15, which depicts four regression lines calculated from quality control test results obtained during normal production of newsprint. Each line relates thickness (corrected proportionately for changes in substance and therefore, strictly speaking, bulk) to Bendtsen smoothness

for results obtained when the moisture content fell within a particular range. (Moisture content was measured as quickly as possible with a portable meter but would be 1 per cent. to 1·5 per cent. higher than the moisture content at the calenders.)

It will be observed from this graph that for a given moisture region an increase in smoothness will on average only occur at the expense of a loss of thickness. This relationship is well known and emphasises the need for compromise when making printing papers for which both smoothness and thickness (or bulk) are in general preferred as high as possible at the same time. However, the point to note is that the relationship between smoothness and thickness at higher moisture contents is such as to cause the thickness to be lower for a given level of smoothness. It appears, therefore, that running at higher moisture content levels, though giving a greater smoothing effect at the calenders, does so only at the expense of a greater loss of thickness than would occur were some quality of the paper other than moisture altered to achieve the same change in smoothness. This, of course, is particularly unfortunate from a papermaking point of view when it is desired to produce a printing paper which is as smooth and bulky as possible.

5A.4 4 Other observations

Some other observations on calender operation which must be mentioned have been reported by Howe and Lambert (61) and by Blanchard *et al.* (82). In both these papers an analysis along similar lines is made of the components of power usage in a stack of calenders. By measuring power input, with and without paper, and making various assumptions and deductions about power losses in the bearings and resulting from stress of the rolls in the nips, it is concluded that only 30 per cent. to 50 per cent. of the total power consumption can be attributed to straightforward work of calendering, i.e. energy absorbed by the paper.

Howe and Lambert interpret their power analysis results as indicating that the fundamental effect of the calenders is produced by 'rolling friction': this is the elastic geometrical compression and distortion undergone by rolls under heavy pressure in the nip regions which creates a small differential in speed between each pair of rolls that will have a shearing effect on the paper. As further evidence in support of this theory the authors cite some results they obtained on roll to roll slippage.

In earlier papermaking books the effect of the calenders was invariably attributed to slippage between the rolls and it was assumed that this created a rubbing or glazing action on the surface of the paper which brought about the increased smoothness. Figures have even been published showing the percentage of slip occurring on calender stacks for different grades of paper. Howe and Lambert set out to assess the importance of roll-to-roll slip by simultaneous differential measurement of the surface speeds of top and bottom rolls in a high-speed stack. The method chosen for this was basically similar to some of the more sensitive and advanced means of draw measurement: it involved the use of discs with projecting teeth fixed to the journal of each roll and serving to generate pulses which

were fed to suitable counters. Many comparisons were made under different conditions with this equipment and in no case when paper ran through the stack was there any significant difference (less than 0·1 per cent.) between the peripheral speeds of the top and bottom rolls observed. With no paper in the stack a difference of a little over 3 per cent. was observed, the bottom roll of course being the faster.

It is probable that older stacks of calenders with greater friction at the bearings could possess a measurable amount of roll slippage with paper running through the stack, but the importance of Howe and Lambert's observation is that this cannot be put forward as the basic source of the calender smoothing effect. To what extent the 'rolling friction' caused by roll distortion is in fact responsible for producing increased smoothness, as these writers go on to assert, is somewhat harder to judge. In the author's opinion, the lack of roll-to-roll slippage, the greater calendering effect obtained under crawl conditions, the observations by Brecht that use of a static 'calendering' apparatus under suitable conditions results in the same smoothness effect (both immediately and also after conditioning) as machine calenders, and finally the visco-elastic relaxation that is known to occur after calendering, all indicate that the change in paper properties is due primarily to straightforward compression. Further confirmation that roll slippage contributes little to calendering comes from an experiment reported by Parker (129) in which it appears that hardly any effect is observed on the smoothness and bulk of paper slipped over a polished steel surface. Also experimental work by Mardon (126) indicates that changes in paper compressibility are a function of the pressure and duration of pressure in the calender nip so that optimum smoothness is best obtained from a stack of small-diameter rolls loaded externally. These points make it seem certain that slip is relatively unimportant except to increase gloss, particularly in supercalendering where fibre rolls are far more flexible than steel and it is thus likely that 'rolling friction' becomes more important.

OPERATING FACTORS AFFECTING DRYING AND CALENDERING

5B.1 STEAM HEATING AND CONDENSATE SYSTEM

The condition of steam supplied to the drying cylinders of a paper machine is intimately related to the overall steam and power system of the mill. This in turn is dependent on local conditions, on whether cheap power is available or whether low-pressure steam can be obtained from an external source, such as a power station. Some mills generate their own electricity and steam in separate units, but a common and highly economical arrangement is to feed high-pressure superheated steam into a turbine or engine and use the low-pressure pass-out steam in the machine house. The main disadvantage of this system is the limit it imposes on the pressure of drying steam available for the machine.

In the machine house itself, steam may be required for a variety of purposes from roof heating to wet felt cleaners. It is the job of the heating and ventilation engineer to determine the most economical method of supplying the various needs according to the temperature and quantity of heat each demands; the installation of heat exchangers on air extracted from the dryer section and on condensate water, the need for make-up steam at high pressure, the optimum temperature of condensate return in terms of the efficiency of running the boilers: these are the sort of questions which can only be decided by a thorough examination of the entire steam and ventilation system.

A detailed discussion of this topic is beyond the scope of this work and only certain aspects are touched on in appropriate places. In this particular section attention is confined to the use of steam on the paper machine in so far as it directly affects the efficiency of production. Steam usage in the ventilation system and in ancillary drying devices will be dealt with in later sections from the same point of view. This is not to say, however, that the economical use of steam is not the concern of the papermaker; in fact the drying section is the main part of any machine where substantial reduction in running costs are possible. A close watch on the overall steam consumption is most important and improvements to the system should be continually sought. Areas of the drying section that repay examination will be given particular attention in the following sections.

5B.1 1 Steam pressure requirements

The steam pressure required for drying depends on a multitude of factors not least of which are the grade and substance of the paper concerned. This question has already been considered in the theoretical section when the influence of such variables as the resistance to transfer of heat from

cylinder to paper and the ventilation conditions were discussed. Thus, an M.G. cylinder is necessarily constructed from appreciably thicker metal than an ordinary drying cylinder and this increases the resistance to heat transfer and so necessitates a higher steam pressure within the cylinder. On the other hand, the use of hoods improves ventilation conditions and reduces the heat needed from the cylinders to achieve a given evaporation rate; steam pressure is consequently reduced.

Increases in speed require greater evaporation rates. When other economical means of increasing evaporation have been exhausted, it becomes necessary ultimately either to add to the number of drying cylinders or to increase the steam pressure in the main supply line. The choice between these two courses will depend on whether a new or existing machine is being considered, but the general tendency these days is towards using a higher steam pressure. This is mainly for reasons of the lower capital cost in terms of equipment and space, and partly the result of a shift in the overall steam and power balance towards proportionately lower power demand compared to steam, thus permitting the use of higher back pressures on the turbine.

Higher steam pressure has several disadvantages: radiation heat losses from pipes and cylinders are greater at the higher temperature, the latent heat of vaporization is lower so that a greater weight of steam is needed to provide the same quantity of heat on condensation, the paper temperature may get too high, and there is more likelihood of steam escaping from nozzles and joints. Further, the balance of steam and power generation suffers considerably from using higher pass-out pressures: Robey and Webzell (97) have stated that an increase in pressure from 20 to 30 p.s.i.g. reduces the steam flow for a given heat demand by 2 per cent. (this assumes a drop to the same final temperature), but reduces the power generated in a typical turbo-alternator set-up by over 10 per cent. Against this, apart from its higher temperature the only real advantage of high steam pressure is that smaller steam mains and valves are needed to carry the same weight of steam.

For some purposes a higher steam pressure may be necessary on a machine regardless of the pressure in the main bank of cylinders. Felt drying cylinders are generally run at a higher pressure because the resistance to transfer of heat from the cylinder surface to the felt is much greater than between a drying cylinder and the paper. Calender heating, to be effective, also requires higher pressures because of the temperatures involved and the high resistance to heat transfer through the thickness of the rolls. In cases where low-pressure steam is used in the drying cylinders, separate supplies are necessary for these purposes.

On the other hand, some parts of the drying section require steam at a pressure lower than that in the main bank of cylinders. The temperature of the first few cylinders which the sheet contacts cannot normally be as high as later cylinders, while at the end of the drying section also it is often considered necessary to reduce the temperature of the paper before it is calendered and reeled; in both cases the pressure of steam in the cylinders must be reduced accordingly. For certain special purposes one set of

cylinders may need to be at a pressure quite different from another set, for example, in curl control where a differential between top and bottom cylinders is required. Such differences can be obtained simply by throttling the main steam pressure at appropriate points (though the question of pressure differential across the cylinders enters here, see **5B.1 4**).

A more permanent arrangement for obtaining lower steam pressure, especially for the first few cylinders, is the cascade system involving re-use of flash steam. This system, though it has altered little over several decades, is a simple and effective way of re-claiming steam blown through the cylinders and extracting as much heat as possible from the steam supplied, thereby reducing the overall weight of steam needed in the dryer. It will now be discussed in some detail.

5B.1 2 Cascade drying system

In the cascade system of drying there are usually two separate flash tanks, though occasionally only one or as many as three tanks are used. Condensate from the main bank of cylinders drains to the first flash tank, and steam from this tank is flashed off at a lower pressure and passes into the second bank; similarly, condensate from this bank of cylinders drains to the second flash tank, and steam from this tank then passes to the third bank. Condensate from the two flash tanks (which are both level-controlled) and from the third bank (which may go through a separator to vent gases) passes to a common receiving tank from where it is pumped back to the boiler under level control. With an M.G. machine the M.G. cylinder itself takes the place of the main bank, and flash steam from the condensate, usually augmented by lower pressure make-up steam, feeds pre- or after-dryers, or is used for heating elsewhere.

To function smoothly the cascade system depends on there being an adequate difference available between the steam pressure in the main inlet manifold and the pressure in the condensate receiver. Where low-pressure steam supplies the dryers, a vacuum pump is needed on the receiver to give sufficient pressure drop.

The actual volume of steam flashed off at both tanks is very small compared to the main flow; for a pressure drop even as high as 10 p.s.i. between the inside of the cylinders (which determines the temperature of the condensate) and the flash tank, the steam flashed off amounts to only a little over 1 per cent. of that entering the cylinders, and this ignores any loss of temperature in the condensate lines. This quantity would normally be insufficient to supply the relatively large number of cylinders that are usually fed by flash steam (the number of cylinders on the first flash tank may be 15 per cent. or more of the main bank, while the number on the second flash tank may be 40 per cent. of the second bank). Without an additional supply of steam the condensing rate in cylinders fed solely by flash steam would be extremely low and the surface temperature could not be expected to be anything like as high as is normally found. In practice, valves on the flash tanks are adjusted to give the temperature required and a certain amount of steam is blown through the main bank of cylinders to augment that available as flash-off.

The more cylinders are placed on flash steam the lower will be their average surface temperature under comparable conditions of pressure drop through each bank of dryers. Too many flash-steam cylinders at the beginning of the drying section can cause the surface temperature to drop so low that sweating occurs even with the flash tank valves open as much as possible. Resort must then be had to using make-up steam from the main bank to increase their pressure, a practice which if permanent requires certain precautions to be taken otherwise the resulting reduction in pressure differential across the main section could lead to waterlogging. This is only avoided by using differential pressure regulators which either prevent the difference in pressure falling below a minimum value, or keep it constant by automatic regulation of a make-up valve between the steam headers of the two sections or by more elaborate arrangements.

Too few flash-steam cylinders, on the other hand, will cause rapid heating-up of the web on the first few cylinders; there is then some danger of the sheet sticking to the cylinders, and of excessive early vaporization which causes the formation of blisters in the sheet. The paper also tends to have a rougher surface when drying is initially rapid and sizing becomes uneven. Despite these disadvantages, when the drying section steam pressure limits production on the machine, it is preferable that as few drying cylinders as possible are operated on flash steam in order to reduce heating-up time of the web and reach the region of constant rate of evaporation early in the drying section.

The most satisfactory compromise is one which suits all the different conditions arising on a machine; once found this is in practice rarely altered, though it is advantageous to have a relatively easy means of switching one or more cylinders onto the main inlet or flash should the need arise. Generally it is preferable to err on the side of having too many cylinders on flash steam provided there is an adequate pressure drop through the system as this seems to give more stable conditions and provide greater latitude in adjusting the pressure drop through each separate bank of cylinders.

The temperature of condensate returned to the boilers is high even when a vacuum system is used, and this can create difficulties at the feed pump to the boilers. It is generally found to be economical to extract as much heat as possible from the condensate before it passes from the machine house to the hot-well, so that in some cases it may be necessary to spray cold water into the condensate receiver to condense any remaining steam and reduce the temperature; this also helps to ensure where main supply pressures are low that the maximum vacuum needed to operate the cascade system can be obtained. Alternatively, heat exchangers are commonly located in the main condensate line, and either water is heated for use in felt cleaning, vacuum pump sealing, fresh-water sprays, etc., or air is heated as it enters the machine house or supplies the make-up requirements of hoods. Flash steam, instead of being used in drying cylinders, may also be utilized in a heat exchanger (this is a popular arrangement on M.G. machines), and many other systems are possible to suit the particular conditions on any machine.

An entirely different drying system which avoids the separate circulation of flash steam involves the use of 'thermocompressors' or ejector-type devices (99). These may either be used singly on each cylinder, or on a complete section; an application of the latter type has been described in some detail by McCaffrey (77) and will be briefly mentioned. With this arrangement, before entering the drying cylinders the main steam supply passes through an ejector which serves to provide the suction to draw out flash steam from a tank into which condensate drains in the normal manner. Three or more individual sections of dryers and a separate one for felt dryers or an M.G. cylinder may be provided, each with its separate main steam supply, ejector, level-controlled condensate tank, and integrated flash system. Each section is set independently to give the pressure desired.

The main advantage claimed for this system is that increased differential pressures can be run across the cylinders, thus aiding evacuation of condensate at high speeds without resorting to an excessive blow-through and without the risk met in a cascade system that sectional pressures are incorrectly adjusted and condensate builds up in some cylinders. Also the system is claimed to be more versatile in that each section is independently adjustable with its own inlet pressure or temperature controller and differential pressure controller; the inlet pressure controllers can, if necessary, be interlocked so that the pressures in different sections are kept constant relative to each other. A strong air-bleed is needed to prevent a build-up of air in the closed eductor circuits, and periodic blow-down of dryers and separators may be necessary.

5B.1 3 Operating a cascade system

It is essential for the smooth operation of the dryers that condensate is removed from each of the cylinders as fast as it is formed; this can only be done by ensuring that there is an adequate differential available between the steam pressure at the inlet joint of each cylinder and the outlet pressure in the condensate line. When operating a cascade system certain precautions are necessary in order to maintain this minimum pressure differential on each cylinder under varied drying conditions; this aspect will now be considered in some detail. The actual magnitude of the pressure differential required, its dependence on the machine speed, the method of condensate removal, and so on, and also the difficulties occurring if condensate is not removed efficiently, are discussed in **5B.3**.

It is important first to appreciate the inter-relation between the heat requirements in the drying part of a machine at any particular time, and the conditions of steam pressure and flow which serve to provide this heat. In the main bank of cylinders a certain pressure is found necessary to achieve the correct drying rate. At the end of the cascade the condensate receiving tank is at an absolute pressure (be this greater or lower than atmospheric) which is set to a value found suitable for normal running conditions. The difference between these two pressures is the total drop available through the system, and must be accounted for in terms of the following: the pressure loss incurred in removing condensate from the

cylinders, the loss in the siphon and condensate pipelines and in the cylinder joints, plus additional losses imposed by valves or orifices in the steam and condensate lines. Each of these pressure losses is in turn affected by the actual flow of steam and water through the condensate system, becoming greater as the flow of either increases, so that in any particular condition both the main steam pressure and the steam flowing to the drying section are mutually dependent in providing the amount of heat required to dry the paper. Further, if the absolute pressure in the condensate receiver is permitted to alter according to conditions, this too will be affected by the pressure loss through the system.

To illustrate this, consider the conditions at start-up when the paper has been fed to the reel and the inlet manifold pressure is raised to a particular value which it is hoped will dry the paper to the desired moisture content. The flow of steam increases until it stabilizes at a level sufficient to cause the total pressure loss through the system to become equal to that available. Suppose that this flow of steam has a heat content in excess of that required to dry the paper under the conditions applying; more steam then enters the main bank of cylinders than can be turned to condensate (the rate of heat transfer being fixed by the pressure in the cylinder) and so an excess is blown through in a condensate/steam mixture, causing the temperature of the flash cylinders to increase and the paper to become too dry. Consequently the inlet manifold pressure would be decreased by throttling the main steam control valve, giving both a lower flow of steam and a reduction in steam pressure (and hence in heat transfer) in all the cylinders. Eventually a pressure can be reached where the heat supplied by the steam flow equals that required to dry the paper.

There are two important points to note in this. Firstly, the lower the overall pressure losses through the cascade system for a particular steam flow, the lower is the drying pressure required to produce this flow. Hence, where a machine is limited in production by the drying capacity, i.e. near-maximum available steam pressure is always being demanded, it is useful to eliminate all unnecessary restrictions in the cylinders, due for example to scale build-up, and of course to have the valves on the condensate lines and flash tanks as far open as possible. This allows as high a steam flow as is practicable for a given pressure in the inlet manifold, thus ensuring that the condensing rate in the cylinders (particularly those on flash) is large enough to satisfy as much as possible of the heat demand from the paper.

The second point is that it is possible for the required flow of steam through the cylinders to be obtained with a low overall pressure drop; in other words, it may be found that the inlet pressure needed to dry the paper is very low. Under such conditions the danger arises that the pressure differential across the cylinders is insufficient to prevent condensate from building up. To avoid this happening it is necessary to increase the total pressure drop through the cascade system by increasing the amount of vacuum on the condensate receiver, throttling the valves on the flash tanks if the temperature of the first few cylinders then becomes too high.

Occasionally the heat demand for a particular grade may be so low that the supply manifold pressure drops below atmospheric. Running under

such conditions is always difficult and drying is apt to become erratic due to air leaking into the cylinders. One remedy is to cut off some of the later dryers (thus increasing the pressure needed in the remainder) but this requires efficient isolating cocks to prevent condensate being drawn back into the cylinders and may cause them to sweat even when only alternate dryers are isolated. Alternatively any supplies of hot air to the dryers could be shut off at the risk of creating problems with the moisture level.

When the drying cylinders are being kept warm in preparation for feeding-up the sheet, as just before start-up or during a wet-end break, the temperature and flow of steam required is very much less than when the machine is running. Consequently steam pressure is set lower. The danger of condensate slowly building up thus becomes greater at this time, especially where the vacuum on the condensate receiver tank is not maintained but is allowed to fall as a consequence of the diminished pressure drop through the system. Though this does not matter particularly as long as the sheet is down, it creates difficulties in feeding-up. When the steam pressure is put back to its normal operating position some cylinders will be slower to clear than others (and, in fact, unless other precautions mentioned below are taken, some may never clear) and the paper will become too damp. The dryerman may then be faced with considerable difficulty as the steam pressure is first increased further to correct this, then decreased as more cylinders are cleared, with the continual danger that conditions are so unstable at some point in the dryers that a break occurs and the whole process has to be repeated.

For this reason it is a valuable provision to ensure that adequate pressure differential is available to keep cylinders clear not only when running, but also when the sheet is not actually on the dryers. If when running normally the conditions are such that sufficient pressure differential is only just available, then almost certainly trouble will occur when feeding up after a break. The remedy is to set the condensate receiver vacuum pump so that adequate pressure differential is always available even when the cylinders are just being kept warm. If it is suspected that the maximum vacuum obtainable is still insufficient to clear cylinders when keeping the dryers warm, the steam pressure must be reduced as little as possible from the normal running value (in other words the outer surface of the cylinders is allowed to get as hot as possible without overheating especially the top bank).

5B.1 4 Maintaining adequate pressure differential across the cylinders

In the previous section, some general comments have been made on operating a cascade system to ensure there is a pressure differential across each bank of drying cylinders adequate enough to prevent condensate building up. To achieve this in practice is far from easy simply because it is by no means obvious when waterlogging is occurring in any particular dryer. It is safe to say that many more machines are run with some cylinders waterlogged than even the most pessimistic papermaker would suggest.

In the first place a substantial difficulty is created by the fact that the evaporation rate, and hence the heat extracted from each cylinder, varies

down the machine. Figure 5.16 illustrates in a typical case the effect of this on the flow of condensate and shows that cylinders at opposite ends of the main bank may condense very different quantities of steam. Yet with group drainage of the condensate lines, each cylinder is subjected to the same overall pressure differential.

For a high rate of condensation, the pressure differential needed to keep the cylinder clear will also be high due to the greater pressure loss in the
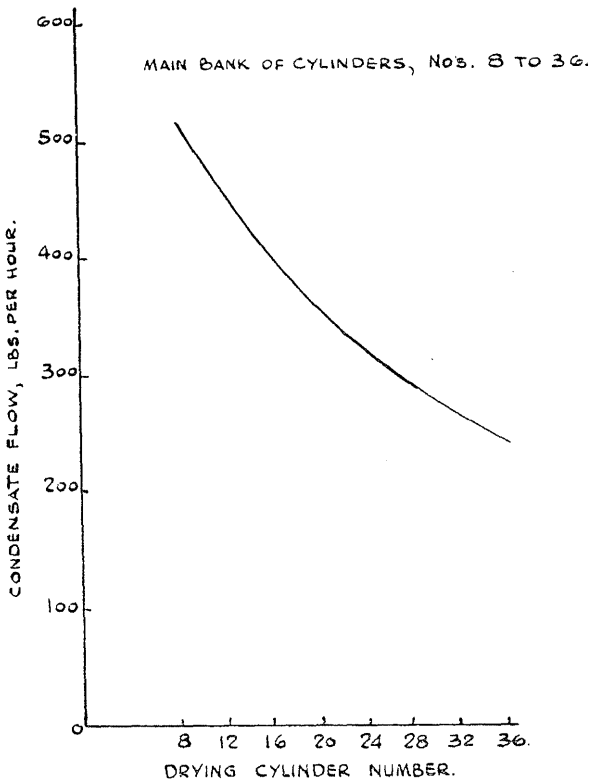
Fig. 5.16. Flow of condensate from successive cylinders on the main steam supply manifold of a paper machine

condensate lines. If the existing pressure differential is inadequate then condensate builds up in the cylinder until the rate of condensation diminishes to a level which can be extracted under the prevailing conditions —in other words the cylinder becomes waterlogged.

On the other hand, for a cylinder with a low condensing rate the existing pressure differential may be too great. In this case it may be expected that a sufficient volume of steam blows straight through the cylinder until the pressure loss of the condensate/steam mixture rises to the level of the

429

available pressure differential. The disadvantage of this is that the large blow-through of steam could tend to raise the pressure in the flash tank, diminishing the total pressure drop available across the bank of cylinders and causing those cylinders with a much higher rate of condensation to become waterlogged.

This state of affairs is avoided by grading the area of siphon tips or, more conveniently, by the use of such devices as orifice plates in the condensate lines from each cylinder. These are sized in such a way that cylinders with a high condensing rate have a relatively open orifice, thus leaving a higher pressure differential across the cylinder, while those with a low condensing rate have a relatively narrow orifice. The dimensions of the condensate lines from each cylinder, and to the flash tank, must of course be ample to cope with the highest rate of condensate flow so that each individual line can be restricted to the extent desired. Provided the relative condensing rate of the different cylinders is approximately known, the orifice plate dimensions can be suitably arranged to reduce considerably the likelihood of condensate building up preferentially in one or more of the cylinders.

Prevention of steam blowing through cylinders with a low condensing rate can also be achieved by the use of steam traps and these are often used on the first few dryers. But, in general, except possibly in the case of scoop-removal of condensate on slow machines, the use of traps on every cylinder is not favoured partly due to their cost and the maintenance needed to keep them working properly, and partly because a certain quantity of steam blowing through is desirable for smooth operation of a cascade system. Further, when using traps on cylinder condensate lines the possibility of steam locking is increased; this is a condition in which steam enters the condensate pipe and trap and effectively blocks off further flow until it has cooled sufficiently to condense. Steam locking can be avoided only by having a release valve on each trap.

The proportion of steam blowing through each bank of cylinders is determined by the overall pressure differential and is generally estimated to be between 5 per cent. and 20 per cent. This amount is thought suitable to ensure that cylinders are kept free from air accumulation and also assists in stabilizing conditions as heat demand from the paper fluctuates during normal running. But a high blow-through increases steam consumption and creates a large drop in pressure in condensate pipe lines. Figure 5.17, adapted from a report by Wahlström and Larsson (109), shows how under various conditions the pressure drop in a 15 ft. long, 2 in. diameter, vertical pipe varies with the percentage of steam added to water flowing downwards. The rapid rise in pressure drop accompanying an increased proportion of steam is of particular significance and indicates that loss of pressure in individual cylinder condensate lines can be of overriding importance when operating with a high blow-through. This point will be discussed in more detail in connection with condensate removal systems. For the moment, it will be noted that the absolute steam pressure is equally as important in determining the magnitude of pressure drop as is the quantity of water involved, and as the steam pressure reduces, the pressure drop

increases appreciably. The implication of this is most important: under comparable conditions of blow-through and condensate flow the pressure loss in the siphon and condensate lines of drying cylinders operating at low steam pressures, in particular of those dryers working on flash steam, can be substantially greater. To reduce the possibility of waterlogging, a greater pressure differential must be made available at lower pressures; thus, the practice of adjusting main valve positions in a cascade system to
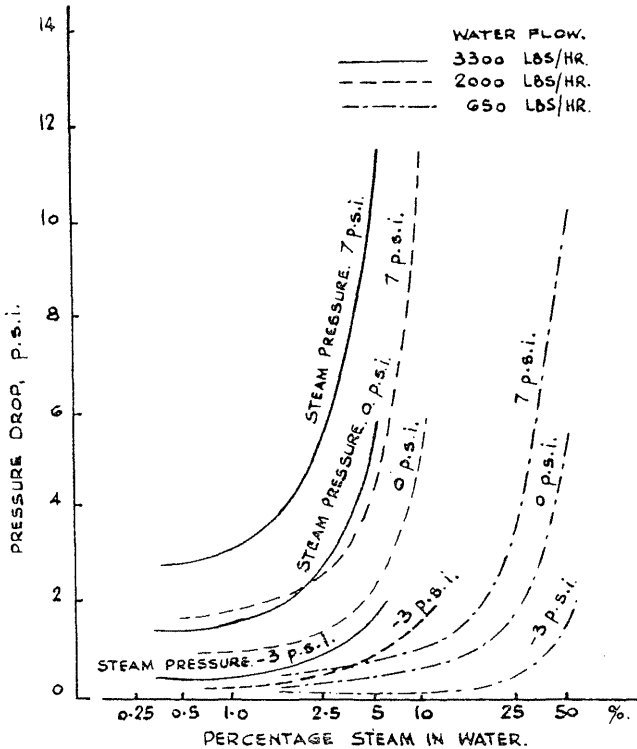
Fig. 5.17. Pressure drop in a downward vertical pipe for various flows of water containing different percentages of steam at different pressures (after Wahlström and Larsson)

give equal pressure drops through each bank of cylinders can be improved by arranging instead for the available pressure differential to increase 2 or 3 p.s.i. in successive banks.

But to be certain that no cylinder is waterlogged it is necessary either to have a differential pressure gauge on each dryer, or to have suitable tapping points for using a portable gauge. Even then, particularly as the exact pressure differential required to evacuate each cylinder is not known and is dependent anyway on the quantity of steam blown through at any time,

there must be some element of doubt that all cylinders are clear unless the system is run in such a way as to have available fairly high overall pressure differentials, and this may be neither convenient nor economical.

Probably the best approach to this problem is to undertake frequent checks of the cylinder surface temperatures using a pyrometer or a non-contacting infra-red radiometer which measures thermal radiation. Though these instruments cannot always be relied on to give a correct absolute measure of surface temperature, they are always useful for comparing the temperature of cylinders one against the other; those cylinders in which condensate builds up have a lower heat transfer, and hence a lower surface temperature, so that comparison with the normal running pattern enables such cylinders to be detected with reasonable certainty. Confirmation of the need for action can then be obtained by comparing the pressure differential across suspected cylinders with the differential across adjacent cylinders off the same bank. Alternatively, the flow of condensate from suspect cylinders can be compared with those from adjacent cylinders, though measurement of this (as discussed later) requires some caution even for comparative purposes because the act of measuring the condensate from individual cylinders is liable to interfere with the natural flow.

Normally if a cylinder is suspected of being waterlogged there is little that can be done until the machine is shut. It may then be noticeable that the cylinder cools slower than the others, showing that is is holding more water, which will be a good indication that removal during running was not satisfactory. The cylinder and condensate removal system would then be opened up for examination, and if these were in sound condition, with no signs of pipelines being rusted up, siphon tips broken, etc., then a change may be made in the size of orifice plate in the condensate line. Possibly it would be useful to have valves in the condensate lines instead of orifice plates to give greater flexibility and permit alteration of the pressure differential during running. But most papermakers would feel uncomfortable about this arrangement unless there were regular, possibly weekly, checks through the whole system.

Sight glasses on condensate lines can also be useful to give an indication as to whether the flow is stagnant, but these are probably too subjective and difficult to interpret to do other than show up really bad cases of waterlogging.

5B.1 5 Condition of the steam

The performance of the dryers is dependent on the condition of the steam and this can vary in three important respects: the degree of superheat, the air content, and the extent of contamination. Practically all machines use steam which is saturated, or very close to saturation. An ideal often aimed at is to pass the steam out with just sufficient superheat to ensure that by the time it enters the dryer supply manifold it is saturated but dry as this minimizes condensation in the pipeline. But for a long time there have been many who advocate the use of super-heated steam mainly, it would seem, because in most integrated steam and power systems it is necessary to

de-superheat the steam before passing it to the machine house, and this is to some extent uneconomical.

Though this may be the case, the weight of opinion is firmly against using steam with any but a moderate amount of superheat. The superheat itself adds little in heat value over and above the latent heat (a superheat of 10 deg. F. gives out approximately 5 B.t.u. on falling to saturation temperature, compared to around 970 B.t.u. latent heat). But the main trouble appears to be that drying becomes erratic with superheated steam, especially in an M.G. cylinder and it proves difficult to control the steam without the occurrence of wide swings in inlet temperature for only small changes in the flow. The reason advanced for the erratic drying is that condensation of the steam inside cylinders is not even: small differences in drying rate across the cylinder cause the temperature at some points to be slightly above saturation and the steam does not then condense in those places. In contrast only a small difference in temperature will condense saturated steam, releasing the latent heat and providing a drop in pressure which helps to maintain circulation in the cylinder.

There is no doubt at all about the detrimental effects of air in the steam. Although feed water passing to boilers is de-aerated, there can still be a small percentage of non-condensible gases diffused in the steam passing into drying cylinders, and if this is allowed to accumulate its presence soon has an effect on drying efficiency. Air can leak in through poorly sealed steam glands in the parts of a dryer subject to a partial vacuum, and also through manhole covers.

For pressures in the region of 10 p.s.i.g. each 1 per cent. of air in the steam reduces the temperature approximately 0·5 deg. F.; this would necessitate an increase of roughly 0·25 p.s.i. in pressure to maintain the original temperature. Thus, 10 per cent. of air would reduce the temperature of 10 p.s.i.g. steam from 239 deg. F. to 233 deg. F., necessitating an increase to almost 13 p.s.i.g. to maintain the original temperature of 239 deg. F.

For this reason it is essential to ensure that air and other non-condensible gases are removed from the whole steam and condensate system. At start-up, cylinders should not be allowed to remain stationary right up to the time when the sheet is ready for feeding up. They should preferably be rotated slowly right from the start, and the steam allowed to blow right through the system and out at suitable vents in the condensate tanks for sufficient time to clear all the cylinders (often such vents contain a thermostatic element designed to shut off automatically when their temperature reaches a suitable pre-set level). During running some form of continuous venting can also be beneficial and, in cases where the main pressure is less than atmospheric, absolutely vital. In systems based on the use of ejectors it is quite common to have automatic venting devices which allow steam and air to blow off when the difference between the actual temperature and the temperature corresponding to the measured pressure exceeds a pre-set value.

Apart from the loss in effective temperature occasioned by the presence of non-condensible gases, the greater density of air (approximately double

that of steam) will create a tendency for it to collect on the cylinder walls where its effect on condensing conditions will be more noticeable. Also there will be a substantial increase in resistance to heat transfer if the air is trapped in an insulating layer between the cylinder surface and the condensed water. To avoid this, Hoyle (88) has suggested that it is essential to have adequate turbulence in the cylinder, and this would also have the benefit of giving a more even distribution of steam within the cylinder. For high-speed machines, in which the condensate is rimming and there is, therefore, little turbulence caused by water movement, it may well be advantageous to follow Hoyle's suggestion of injecting steam into the cylinders on to special baffles or some other device which will assist its dispersion.

The growth of scale and rust in the drying cylinders and steam and condensate lines can create difficulties over a period due both to the unevenness and overall reduction which occurs in heat transfer through the cylinder, and to the increase in pressure drop occasioned by roughening and narrowing of the pipe-lines and fittings. The use of filming amines in steam is reported to prevent this in drying cylinders by forming a non-wettable film on the cylinder surface which protects against the attack of oxygen and carbon dioxide in the steam. A further benefit stated to follow from using filming amines is that at lower speeds of rotation condensation in a dropwise fashion is promoted and this, by making it more difficult for an even film of water of high heat-transfer resistance to be formed, helps to create better conditions of heat transfer over the cylinder surface.

Schoonen (55) has given a summary of the results of using filming amines on various machines and mentions that increases in production of from 5 per cent. to 15 per cent. have been claimed as a result of improvements in heat transfer. But even though an increase in heat transfer was confirmed in a laboratory experiment, a mill trial over four weeks on two slow machines was not successful, and no improvement was observed which was significant compared to normal operating variations.

The amine also acts as an inhibitor to corrosion and when applied to a surface already corroded it penetrates under and loosens existing corrosion products. If too large a dose is introduced into the system at first, there is a danger that steam traps and other constrictions in the condensate lines become clogged. Addition of filming amines is generally into boiler feed water and must be continuous or former conditions soon return. As with any other additive the economic value of its use should be carefully assessed, though this requires accurate knowledge of the evaporation rate and efficiency of the drying section.

5B.2 FELTS AND FELT DRYING

The purpose of felts in the drying section is mainly to increase the evaporation rate and reduce the overall cost of drying. Which type of felt in each section of a particular machine best satisfies this objective, whether indeed a felt makes any improvement at all, are questions to which the papermaker

should require an answer. Unfortunately, it is generally the case that felts are selected for their performance in every other respect but these.

The reason for this is that on the vast majority of paper machines there is a basic lack of information on the performance of the dryers. Commonly, a pressure gauge on the main steam manifold is all that the papermaker has to guide him and this, though useful as a rough indication of general drying conditions particularly when the available pressure limits production on the machine, is of little value on its own in assessing whether the substitution of a new type of felt over one bank of cylinders has brought about a significant improvement. The papermaker cannot, therefore, be blamed for choosing his felts primarily for their running qualities: resistance to wearing, lack of shedding fibres, ease of guiding, absence of mark on the paper, good dimensional stability, and so on.

The difficulty of obtaining useful comparative data is apparent when the literature is searched on the subject of dry felts. One of the few attempts to get operational data about performance, the B.P.B.M.A. Technical Section questionnaire in 1958, produced absolutely nothing. The benefit of felt dryers is an even more obscure subject. The section that follows gives a brief summary of the available published information.

5B.2 1 General comments on different types of dry felt

Dry felts used to be made mainly of wool, frequently woven endless like wet felts. Nowadays the length of dry felts usually necessitates seaming, and wool is not so favoured except under extremely acid conditions because of its tendency to shed dust as it ages. Difficulties in keeping an even tension also frequently arise due to the varying degrees of shrinkage that occur at different places across the machine, particularly at the edges. On some machines dry felts containing asbestos are used where very high temperatures are involved, but until comparatively recent years pure cotton in a variety of weaves was probably the most popular basic material, at least on faster machines. The main advantages of cotton have always been its cheapness, strength, dimensional stability, and good resistance to abrasion, though it gives a coarser surface.

The appearance of synthetic materials has radically changed the situation. Dry felts are now reinforced with nylon and terylene in various ways in the body of the yarn and in separate yarns, or occasionally felts are made exclusively from synthetic materials in various blends; their high strength, flexibility, dimensional stability, and resistance to heat and other contaminants have brought about many beneficial extensions in life. Race (49) has shown that synthetic materials absorb water more rapidly and with less fibre swelling than cotton (thereby retaining their permeability to moisture better). Also he has demonstrated under a variety of experimental conditions that synthetic felts dry comparatively quicker. This has been confirmed by Bowden (32) who observed a reduction in steam usage in a hot-air felt-drying system when a terylene felt was substituted for a wool one on an M.G. machine.

The use of felts containing synthetic materials is nonetheless highly individual to machine conditions, and in some cases they may at best

serve only to give an extended life. In this respect Race states that felt life is increased on average 2 to 3 times when replacing wool by synthetic felts on slow fine-paper machines (giving a similar cost per ton), but replacement of cotton felts on faster machines usually shows substantial economic improvement. An improved evenness of drying across the sheet, less dust, and lack of trouble with contamination of oil on the edges of felts (because synthetic materials absorb oil less easily) are other advantages claimed. Failure of terylene felts is often due to hydrolysis followed by mechanical degradation, so that when used over early dryers under damp conditions, felt dryers, or the use of one cylinder for drying the felt instead of paper, are essential.

In recent years the advent of plastic fabric dry felts or dry 'wires' has brought about a further development which has been very beneficial, particularly on faster machines. Here the advantage is generally less one of giving extended economic life, so much as improving the drying rate and efficiency. Especially when used in early positions in the drying section, fabric felts may be found to give a big improvement and, because they do not hold water, less trouble is likely from damp streaks emanating from the felts. Also they do not shrink or expand in use, and can be cleaned with water or low-pressure steam. However, in some installations troubles with wrinkling of the fabric, especially at the seam, has been reported. Marking of the sheet does not appear to be a problem.

The type of felt which best suits a particular situation on a machine obviously depends on many factors. Careful comparison of the performance and the conditions prevailing with different dry felt types and materials in each position of a drying section is most essential, though of necessity each trial is extended over a long period. This subject is dealt with in greater detail in 5C.2 2, and attention is now turned to examine what pointers there are indicating which type of dry felt is best in different conditions from the point of view of drying rate and efficiency—the most important criteria, yet on most machines the most difficult to assess.

5B. 2 2 Specific comparisons between different felt materials

There have been only two comprehensive reports of investigations in which direct comparisons of different types of felt have been made, one using an experimental set-up and the other an experimental machine. The results obtained will now be considered.

B. W. Attwood and S. F. Smith (1, 7) devised an apparatus for experimental simulation of drying conditions which represents the first attempt to obtain some fundamental data. In this apparatus samples taken from the press of a board machine were dried in contact with a heated, curved metal surface in a manner designed to simulate as closely as possible the sequence of events in the drying section of the machine. The sheet was successively pressed into contact with the heated surface by a felt, released and reversed through 180 deg., exposed to moving air, then placed with the opposite side in contact with the metal surface, the whole cycle being repeated as often as necessary. The tension at which the sheet and felt were held, the temperature of the heated surface, the condition of the air blown onto the

436

sample, the pressure of contact onto the drying surface, the length of time in each cycle that the sheet was in contact with the surface and expoeds to the air, and the number of drying cycles could all be varied. Conditions of drying were in the first place selected to correspond so far as possible with those observed on the board machine; the air velocity was set equal to the machine speed.

By weighing the samples after a given number of drying cycles (corresponding to passage of the web over so many pairs of dryers) a drying curve could be constructed to show reduction in moisture content from the initial value of around 65 per cent. In general, excellent agreement was found with the equivalent machine drying conditions in terms of lbs. of water removed per square foot of dryer surface per hour. The more obvious differences in detail between the experimental and the actual methods of drying were that the felt itself was not dried and only one was used, and also the temperature of the heated surface remained constant.

Amongst their various experiments, Attwood and Smith made a direct comparison (with other conditions constant) of the rate of drying with felts made from several different materials, viz. wool, cotton, cotton/asbestos, linen, wire cloth, and linen faced with tinfoil to make it impermeable to water and vapour. The drying rates with each of these types of felt varied surprisingly little from each other, considering the wide difference in characteristics between them. But of those tested the permeable materials, wire cloth and linen, showed the highest drying rates, while wool and cotton were practically identical, cotton/asbestos slightly worse, and the tinfoil-faced felt by far the worst. It may also be noted, although the differences concerned are small, that of the two best materials the wire cloth gave slightly the better drying rate in the early drying cycles when the board samples were damp, but that in the later cycles the drying rate was faster with the linen felt.

The other investigation in which different felts have been compared was part of the extensive work referred to earlier which was carried out on the Swedish Central Laboratory experimental machine; this has been reported by Ponton (47). In this experiment the moisture control of paper entering an M.G. cylinder was varied, and the water evaporated over the cylinder for each condition was determined. A direct comparison of the performance with different types of felt (run for this purpose at the same tension) was thus possible.

Figure 5.18 shows the quantity of water removed from the web after passing over the M.G. cylinder with various types of felt, viz. wool, cotton, terylene, takryl, perlon (nylon) wire, and without any felt, in each case for different moisture contents entering the M.G. cylinder. The line passing through the origin represents the quantity of water in the web entering the cylinder, so that the vertical distance below this line represents the water remaining in the web under the various conditions. In Fig. 5.19 the total steam consumption (in both the M.G. cylinder and a felt dryer) is related to the water removed from the web.

These results show first that when the web is comparatively damp entering the cylinder, the type of felt does have a pronounced effect on the

water removed. In this case wool and cotton felts gave the best water removal with the perlon wire only slightly worse for the dampest conditions. When a considerable quantity of water has to be transported away the ability of the wool and cotton felts to take up and retain this water is thus advantageous; once the quantity of water requiring removal has fallen, with adequate ventilation the wire-type felt appears to give a similar performance. Furthermore, reference to Fig. 5.19 shows that the wire-type felt required a lower steam consumption, i.e. gave a higher efficiency of steam utilization, despite the fact that in the experiment steam in the felt dryer was kept at a controlled temperature although this was not required
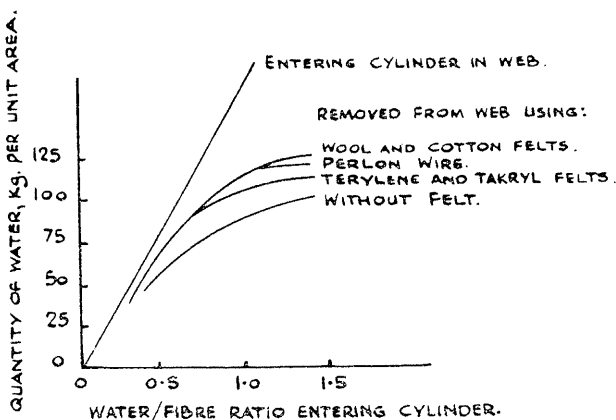
Fig. 5.18. Comparison of water removed on M.G. cylinder with different types of felt (after Ponton)

for drying the wire. Synthetic felts removed a significantly lower quantity of water, possibly because they are less able to take up water than cotton and wool felts, yet offer similar resistance to the passage of water vapour. Without a felt the drying capacity was severely reduced, though overall less steam was required to dry the paper.

When the paper was drier entering the cylinder, the difference between the various types of felt diminished until at about 0·6 water/fibre ratio (37 per cent. moisture) it ceased to exist altogether. This confirms the reduced importance of the felt in governing the rate of water removal in later stages of drying, though the results also indicate that the drying capacity will nevertheless be greater than without any felt, presumably due to the better heat transfer condition across the cylinder/paper interface. Further support of the diminishing rôle of dry felts as the paper becomes drier may be adduced from the results obtained by Jepson (90) when he observed the effects of removing dry felts from a number of machines: in all cases reduction in drying rate was much greater when felts in the early positions were taken off.

In a further experiment, Ponton compared the performance of two wool
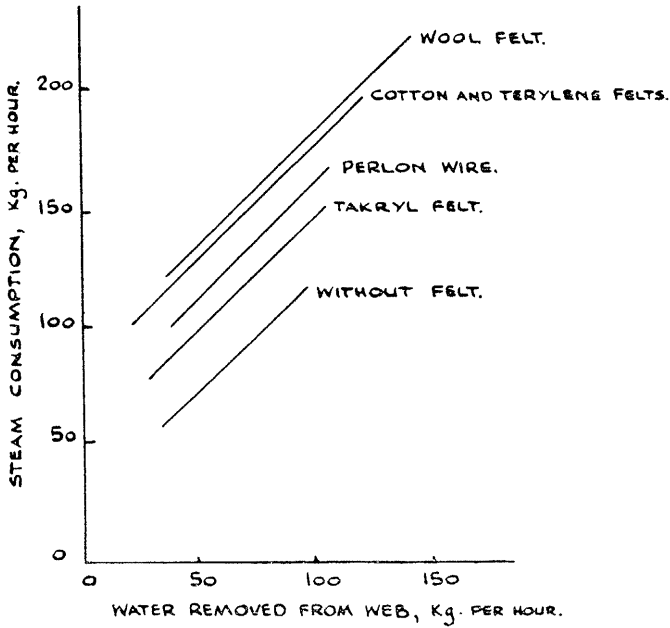
Fig. 5.19. Steam consumption related to water removed from web on an M.G. cylinder with different types of felt (after Ponton)
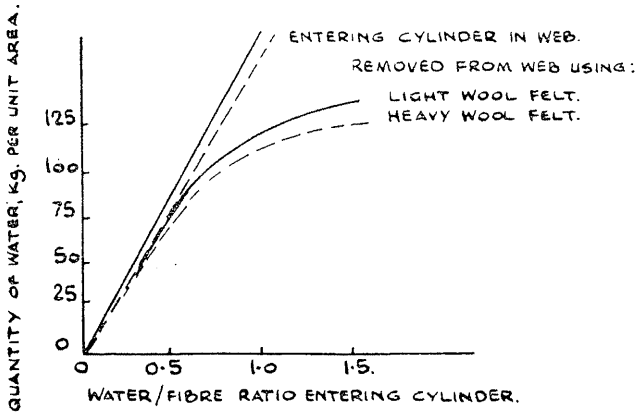
Fig. 5.20. Comparison of water removed on M.G. cylinder using a light and a heavy wool felt (after Ponton)

felts, one of basis weight 3,500 grams per sq. metre, the other 2,100 grams per sq. metre. The results, represented as in the previous comparison, are shown in Figs. 5.20 and 5.21. The thinner felt not only gave a higher rate of water removal, but did this at a higher efficiency of steam utilization. The difference in performance with the web entering the cylinder damp is clearly significant, and is probably due to the greater drying effect of the felt dryer on the thinner felt combined with a lower resistance to the passage of water vapour. It might be thought that a thinner felt could get
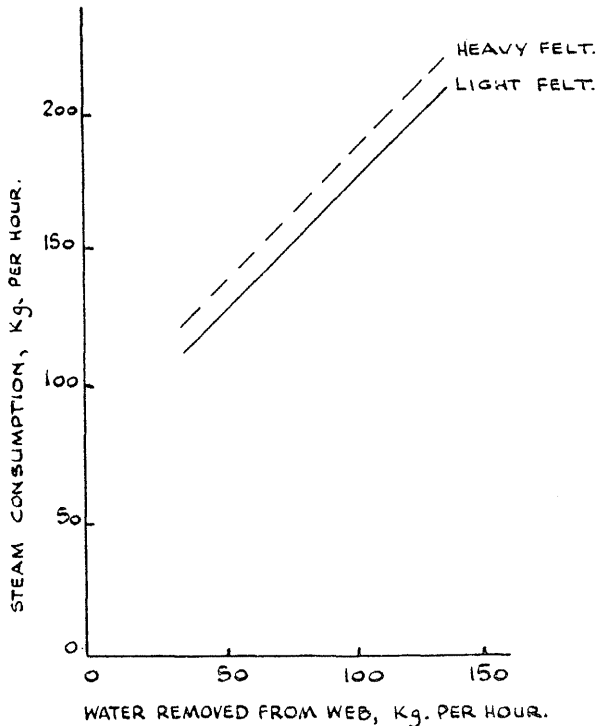
Fig. 5.21. Steam consumption related to water removed from web on an M.G. cylinder with a light and heavy wool felt (after Ponton)

saturated easier and cease to remove any more water, but in practice if this were likely to occur a greater felt drying capacity would be called for.

Finally, an isolated but careful comparison by Bowden (32) of the performance of two dry felts on an M.G. cylinder is worth mentioning. In this work it was clearly shown that a wool felt removed more water than a terylene one under quite a wide range of running conditions and despite the fact that the cylinder surface temperature was invariably greater with the terylene felt.

To summarize, over the first few cylinders, and particularly when the

440

paper is very damp entering the dryers, the fastest drying rate is likely to be achieved with natural-fibre felts. This is provided the felt is kept sufficiently dry, which means provision of adequate felt dryers and the use of lighter weight felts. If the web is not unduly damp entering the dryers (which should be the case if the presses are used properly), and the ventilation conditions are good, then a plastic fabric dry felt may be expected to give as good a drying rate as felts made from natural fibres, and possibly better if there is no felt drying equipment on the machine. The choice can be seen to depend essentially on which type of felt is best fitted in the prevailing operating conditions to accept and remove the water vapour driven off the web—with good felt drying provisions and when the web is so damp that liquid transfer to the felt is possible, then natural fibres will be better; with a well-ventilated hood the plastic fabric should undoubtedly be best. Furthermore, plastic fabric dry felts may well have a slightly higher steam utilization efficiency and so be more economical to use.

Towards the end of the dryers the felt itself has to cope with much smaller quantities of water vapour and it is more important to keep the temperature of the web high. Provided the resistance to heat transfer between cylinder and paper is kept as small as possible by applying adequate tension to the felt, the actual type does not appear greatly to affect drying rate and efficiency. In this region the other factors for comparison of one felt with another, such as economic life on the machine and dimensional stability, become more important criteria.

On machines making very heavy substances such as paperboard, adequate tension can often be applied to the web to achieve the close heat contact with the cylinders that it is the primary function of the felt to assist; in such cases felts can be dispensed with altogether, and provided the drying rate is adequate this could well be highly economical both in eliminating the whole cost of felts and in giving a better steam utilization efficiency. Normally sufficient drying capacity is only obtained by felting all dryers except the pony cylinder; in cases where a comparatively gradual heating-up period is thought necessary the first one or two full-size cylinders may also be unfelted.

5B.2 3 Felt tension and arrangement on the dryers

While the material and construction of dry felts have by far the most important influence on performance of the dryers, there are some other aspects relating to the felts which require consideration, in particular the tension at which they are run and the manner in which they are arranged over the dryers.

It is commonly believed that increasing tension in a dry felt, at least up to a certain point, will improve the drying rate; this is a consequence of the closer contact reducing resistance to transfer of heat from the cylinder to the web. Evidence that this is so has been reported by Smith and Attwood (7) from work on their experimental apparatus, and by Bowden (32) who found that tightening a terylene felt over an M.G. cylinder from a very slack tension increased water removal by about a quarter.

However, Ponton (47), in the experiment on the Swedish Central

Laboratory machine, could detect no change in water removal occasioned by altering the tension. Although Ponton's work covered a wide range of ingoing moisture conditions, from water/fibre ratio of 0·4 to 1·3, Smith and Attwood's board samples were initially at a ratio of 1·7, and the ingoing water/fibre ratio in Bowden's work averaged 2·4. The differences in moisture content of the web are thus the most probable reason for the discrepancy in the results, and within limits tension may only have a really significant effect on drying rate in the early part of the drying section when the web is quite damp. Possibly (as suggested by Nissan) the effect occurs only when there is some transfer in a liquid state and tighter tension induces a sustained pressing action on the web.

Except for the dry felts covering the first few cylinders, there thus seems to be no reason to apply a tension which is at all heavy. The greater the tension, the more the felt is likely to distort or crease under adverse conditions of moisture change such as occur opposite a wet streak or at a break. It is also probable that a felt run slacker will have a longer life. Occasionally, other considerations may require heavier tension in a dry felt, for example when it is desired to keep shrinkage of the paper to a minimum, or when some cylinders are not geared and are dependent on the felt to drive them. Otherwise it is probably more important to ensure that tension is even across the width of the felt in order to reduce the chance of creating an uneven drying rate in different parts of the web.

The wrap of a felt over individual cylinders should be as great as is practicable, a requirement that is always met with in the building of a dryer section. Apart from this the question arises, how many felts to use and where to break up the different sections?

With the usual double bank of dryers, for convenience of arranging the drive gears it is obvious in the first place that different sections are best divided along the top and bottom in the same way. The two dry felts over the first few dryers are the most critical and must cope with most water removal. These should therefore be comparatively short and cover no more than four or five cylinders each, preferably less. If a drying section has been arranged with many more cylinders than this in the first section, it is unfortunately a complicated matter to reduce the number to see if this brings an improvement; the only alternative is to ensure the provision of adequate felt drying facilities and in the absence of these an improvement is very likely if the dryers can be made to run with one of the middle cylinders of the section used solely as a felt dryer.

How many sections there are following the first depends on the total number of dryers and the need to regulate machine direction shrinkage. Often there is only one further section, making four dry felts in all, but on longer and faster machines further sections may be used to keep the dry felts to a reasonable length. When this is the only consideration, the length of each individual section should be made progressively greater towards the dry end of the machine.

On certain speciality machines, and machines with an M.G. cylinder in the middle of the drying section, it is common to divide the dryers into as many as six or seven different top and bottom sections. This is necessary,

for instance, where extensive shrinkage occurs in a paper during drying, or when it is essential to have an accurate control on the amount of shrinkage that can take place. Each individual section will have a separate drive with relative speed control to allow the draw between the sections to be set. Where Sheehan ropes are used to feed up the tail, these also have to be split into the same sections.

5B.2 4 Felt drying equipment

The importance of keeping felts dry, particularly when they are made from natural fibres and pass over the first few dryers, implies that in certain circumstances some form of felt drying equipment is essential to maintain a good rate of drying and efficiency. The small-diameter heated cylinder is one popular method of drying felts, and to be effective the steam pressure in this cylinder should be greater than in the main drying cylinders to allow for the higher heat transfer resistance. The face of the felt contacting the paper, being the one into which moisture is driven, is made to contact the surface of the felt dryer.

Other types of felt drying equipment utilize hot air blown through nozzles directed straight on to the felt or through a rotating perforated roll over which the felt passes. Alternatively the felt may pass over a perforated or wire-covered roll to which suction is applied drawing the warm moist air of the drying section through the felt. Equipment of this type is usually more suitable when plastic fabric or relatively porous dry felts are used, especially synthetic which hold water mainly by adsorption.

Various claims are made regarding the advantages of using each of these types of felt drying equipment, but unfortunately generalization from individual applications must be highly suspect. Apart from improving the evaporation rate and drying efficiency, an increase in the felt life and more uniform drying across the web have also been observed when felt drying equipment is first introduced. On the first top and bottom felts, two or even more individual felt dryers may be used, one immediately before the dry felt meets the first cylinder, the other halfway or less along the felt run. To introduce a felt dryer in the middle of a felt run between cylinders can involve a slight increase in the spacing to allow two felt rolls to be used, and occasionally difficulties occur in keeping the felt running smoothly and preventing a slack draw to the sheet.

The usefulness of any felt drying equipment requires checking and perhaps the easiest way of doing this on a comparative basis is simply to turn off the steam supplied to the dryer and observe what happens. It is, however, not always easy to assess the significance of any changes that occur, and it is preferable whenever practicable to divert the felt dryer steam into the main drying cylinder manifold keeping the position of the main flow control valve fixed. Changes in moisture content of the paper at the reel-up should then indicate, other things being equal, whether the extra steam in the felt drying equipment is being used to the best advantage; note, however, that it may take up to an hour before complete equilibrium under the new conditions is established.

Little work even of a simple comparative nature has been reported in the

443

literature. Jordan (10) mentions that he found two felt dryers at the dry-end of a machine (also well provided with a flow of hot air to the felts) were not necessary; in fact, it appeared that moisture uniformity across the web was better without them. Although no details are given it is probable from other data in the article that a measure of the steam consumption was used as a basis for this comparison.

Rogers and Webster (20) have also reported some work on felt dryers in which they measured the moisture content of a dry felt by using a beta-ray gauge. They found that reducing the steam pressure in the felt dryers from 35 to 19 p.s.i.g. caused the dry felt moisture content to increase, although only from 2·9 per cent. to 3·1 per cent. moisture. In a second experiment, removal of one of six felt dryers caused an increase from 4·3 per cent. to 4·5 per cent. in the felt moisture content, but removal of two of the dryers caused a much greater increase to 5·4 per cent. moisture. It is difficult to assess the importance of these figures but some spot comparisons indicated that the modifications had no significant effect on the moisture content of paper at the reel-up. It may be remarked that the magnitude of changes measured in the dry felt moisture content appear relatively small, and on a felt with the normal one or two felt dryers the effect of making similar alterations will probably be much greater.

The use of hot-air blowing felt rolls in association with plastic fabric dry felts has been reported by Jender and Gavelin (124) and Race *et al.* (130). Improvements in moisture profile were noted in both cases, and in the latter work some success was obtained in controlling the profile by altering the position of air flow through the fabric. This approach depends more on changing the ventilating conditions within cylinder pockets than on actual felt drying, and as such is not so suitable when used with conventional dry felts.

5B.3 CONDITIONS INSIDE THE DRYERS

Drying cylinders provide a simple and relatively trouble-free means of transmitting heat from steam to paper. But to work effectively, steam must condense evenly over the inside surface of the cylinder, and the heat released should meet as little resistance as possible as it is conducted outwards. Fulfilment of these requirements is considered in this section.

5B.3 1 The behaviour of condensate in the dryers

It is most important for satisfactory operation of any drying cylinder that the condensed water should be removed quickly and steadily. Water allowed to collect in a dryer has several disadvantages depending on the speed of rotation. At relatively slow machine speeds up to 400 or 500 feet per minute, condensed water simply forms into a pool at the bottom of the conventional size of drying cylinder, and the greater volume this pool occupies, the less is the effective area where condensation can occur on the inside surface. This is likely to be especially detrimental in bottom cylinders where the web wraps round the region where the pool forms.

At higher machine-speeds the pool of water begins to climb up the side of the cylinder producing a growing amount of churning and cascading.

This introduces an unevenness in operation which affects the smoothness of rotation (and hence the draw between cylinders), and is particularly noticeable for the fluctuations it can create in the power required to drive the cylinder.

At even higher speeds, above 1,000 feet per minute, the phenomenon known as 'rimming' occurs when the pool at the bottom of the dryer vanishes and water spreads in an even layer round the whole inner circumference. This condition is characterized by a much steadier rotation and power demand, but the layer of water between the steam and the cylinder surface represents a substantial resistance to the transfer of heat so that a greater steam pressure is needed to achieve the same drying rate.
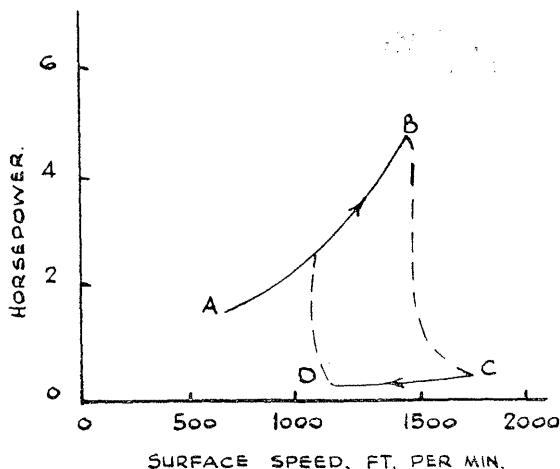
Fig. 5.22. Relation between power required to rotate drying cylinder and the speed of rotation, for a fixed volume of water in the dryer (after Cooke)

The behaviour of dryers as the speed of rotation is increased through these different phases has been illustrated in some interesting data presented by Cooke (9) and White (26). Both workers used a single experimental cylinder in which they could observe the motion of a known volume of water and measure the power consumed at different speeds of rotation.

Figure 5.22 from Cooke's paper shows the change in power found necessary to rotate a 5 foot diameter cylinder at increasing speed when it contained a fixed volume of water (in this experiment there was no siphon action and frictional losses at the bearings were allowed for). The line A B represents the growth in power consumed as the water became increasingly turbulent; at B rimming occurred, and the power dropped rapidly until at C it was practically zero. Reducing the speed gave the effect shown between points C and D; the rimming condition collapsed at a lower speed than it formed at, the power consumed jumping to its previous high value.

Increasing the volume of water in the cylinder made no difference to the general shape of the curve shown in Fig. 5.22 except that the rimming

445

velocity increased, and the power consumed at any particular speed in the turbulent region was always greater. The increased power required when the volume of water is greater, coupled with delay in the onset of rimming, causes the power consumed at its maximum point (immediately prior to reaching the rimming condition) to increase substantially. For example, maximum power demand for 100 lb. of water in the cylinder was under 2 h.p.; but in Fig. 5.22, which related to 175 lb. of water, the maximum power demand increased to 5 h.p. Thus, speeding up a machine through this critical region may well become hazardous to achieve smoothly if many cylinders contain comparatively high quantities of water.
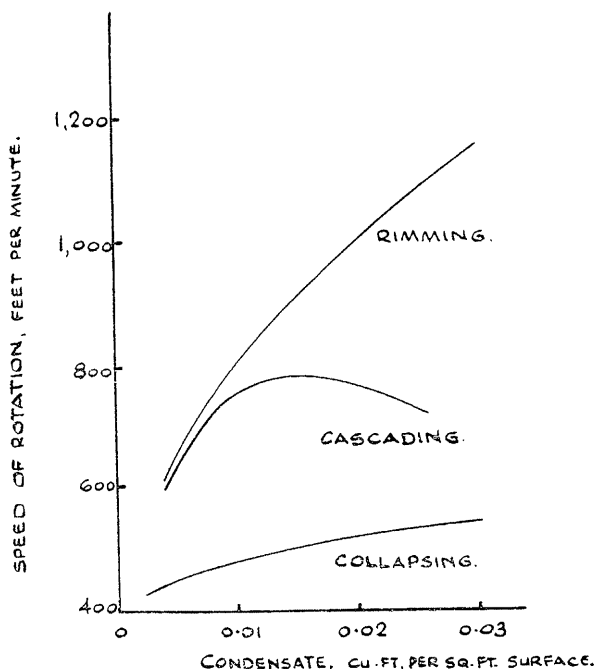
Fig. 5.23. Speed of rotation of a 1 ft. cylinder at which cascading, rimming, and collapse of rimming occur for different volumes of water in the cylinder (after White)

In a further investigation Cooke kept the speed of rotation of the cylinder at a high value while increasing the volume of water to the point where rimming broke down. When this occurred there was the same violent jump in the power demand. Also the greater the speed used, the more water could be held in the rimming condition before this broke down, e.g. 0·14 in. depth at 1,010 feet per minute, 1·1 in. at 1,310 feet per minute.

White followed a similar experimental procedure, though on a 1 foot diameter cylinder, and his observations agree closely with those of Cooke. Power demand in the cascading region was found to be erratic, and the same abrupt drop occurred when rimming commenced. On reducing

446

speed, the transition from a rimming to a cascading condition was also sudden, but smoother. Figure 5.23 shows for varying volumes of water the speed of the drum at which cascading first began, and also when rimming and (on slowing down) collapse of the rimming condition occurred. Though these curves refer, of course, to the 1 foot diameter cylinder, other data indicate that so far as the rimming curve is concerned the corresponding values for a 5 foot diameter cylinder would be approximately 1·5 times as high.

White reports that even at very low speeds of rotation there was a thin film of water on the inner surface of the cylinder the thickness of which grew with increasing speed. When cascading occurred, it did so in bands across the cylinder (similar in appearance and origin to the curtains observable under a table roll) and involved only a relatively small volume of water. The rimming condition started at one or other end of the cylinder, spreading quickly across the cylinder.

It is apparent then that under all conditions it is beneficial to keep the volume of condensate in a dryer to a minimum: at low and medium speeds primarily because of the effect of a greater volume on the power consumption and evenness of operation, at high speeds primarily because of the greater resistance to heat transfer through the cylinder offered by a thicker layer of water. In the speed region where rimming may occur, the situation is rather more complicated.

In the first place, the critical speeds for the commencement and collapse of rimming depend on the volume of condensate in any particular cylinder, and hence vary from cylinder to cylinder down a drying section due partly to differences in the rate of condensate formation and removal, and partly to other factors such as roughness of the inner surface. Alterations in speed through the critical region will thus produce a series of surges in power demand as individual dryers change their condition; these surges will in turn increase the likelihood of a break in the drying section as momentary impulses are transmitted to the tension of the sheet in the open draw between cylinders.

Where a machine operates in the speed range between roughly 1,000 and 1,600 feet per minute, these difficulties are very likely to occur at one or other point of the dryers. For speeds at the higher end of this region fluctuations are likely to be particularly severe, and it would be prudent to try to avoid the cascading condition altogether by increasing the steam pressure immediately prior to feeding up the sheet, and temporarily speeding up the drying section to well above that required. By this means water in all cylinders is likely to be brought to the relatively stable rimming state characterized by points C to D on the curve in Fig. 5.22. Whether this is satisfactorily achieved in practice could to some extent be judged from the overall power demand of the dryers, which should become relatively low.

The growing thickness of the water film in a dryer as machine speed increases in the lower range implies a progressive increase in resistance to the transfer of heat through the cylinder, necessitating a higher steam pressure (with its attendant disadvantages) to achieve the same drying rate. There is some dispute about the extent to which the heat transfer resistance

447

does increase, some contending that convection currents are set up in the water layer which act as a means of transferring the heat far more effectively than occurs with pure conduction through water. It has even been suggested that a reasonably rough inner surface such as occurs with a thin layer of rust may be beneficial because it is likely to encourage turbulence within the water film, thereby inducing such convection currents. In any event, there is little doubt that the thicker the water layer against the cylinder surface, the higher is the overall resistance to heat transfer, and this will be particularly noticeable in the transition to a rimming condition where the layer will increase in thickness and become more stagnant in relation to the surface.

For these reasons, on some machines running in the critical speed region it may be preferable to avoid the rimming condition so far as possible, rather than encourage it to keep the power demand down. Such a decision must be individual to the machine and though some latitude is available, in that for instance the setting of siphon tips affects the volume of condensate held in a dryer and hence the rimming speed, the whole business of assessing whether and in which cylinders rimming is likely to occur becomes rather a complex matter, inevitably involving much guess work.

5B.3 2 Extraction of condensate from the dryers

In old, slow machines the common method of removing water from the drying cylinders is by scooping it out in a specially-shaped spiral groove fixed to the dryer at the back side. No pressure differential is required to remove water by this means, but of necessity a pool of water must accumulate in the bottom of the cylinder before the rate of extraction can equal the rate of condensation. The efficiency of removal has been found to depend greatly on the design of the scoop (50) and as speeds increase the size of the pool grows until a point is reached where this method of condensate removal severely limits the drying rate. A further difficulty is that if the cylinders need to be stopped no water can be removed from each dryer until the pool has crept up to the level of the journal; on re-starting a heavy and erratic load is placed on the drive and a long time may be required to get the surface temperature of the cylinders up to their normal operating value.

These disadvantages become very evident at speeds around 400 to 500 feet per minute, and above this the scoop is generally replaced by the stationary siphon. With this device a pressure differential is required to lift the water up to the journal, to which losses along the siphon and condensate piping, and the drop in pressure in the cylinder caused by condensation of the steam must be added. From estimations of these losses, it used to be considered that an available pressure differential of from 2 to 3 p.s.i. between the steam inlet and condensate outlet pipe should be adequate to ensure evacuation. However, the results obtained by Wahlström and Larsson (109) referred to earlier have clearly shown that with a normal amount of blow-through steam pressure losses in the siphon and condensate pipes are of much greater significance than had been hitherto suspected; in fact, 2 to 3 p.s.i. represents the minimum pressure differential

suitable under common operating conditions, and especially at low pressures the available drop required to maintain a reasonable flow of blow-through steam and reduce the possibility of waterlogging should probably be at least 5 or 6 p.s.i. across each cylinder.

The siphon itself is frequently just an open-ended pipe dipping to within a fraction of an inch of the inner surface of the cylinder. The pool of water collecting at the bottom tends to be pulled up the side of the cylinder, so it is useful to offset the siphon a few degrees from the vertical in the direction of rotation; this places the tip more centrally within the pool and thus reduces the volume of water allowed to collect. As machine speed increases the impact of cascading water on the stationary siphon tips becomes much greater until with a rimming condition the velocity of impact equals the machine speed. This affects the power consumption and in the rimming condition could also create uneven heat transmission opposite the siphon tip due to disturbance of the water layer. To reduce the impact and take advantage of the velocity generated in the water, specially shaped siphon tips are made which open in a wide horizontal slot towards the direction of rotation and are designed to guide the water into the pipe as smoothly as possible. A further improvement in this direction has been achieved in one type of stationary siphon (Cowie) by attaching a piece of neoprene to the bottom of the tip which scrapes against the cylinder surface. The design of siphon tips to provide efficient condensate removal is a task requiring the specialized knowledge of a steam engineer; a good survey of the problems involved will be found in reference 131.

When water in the dryer is rimming, the setting of a stationary siphon tip in relation to the cylinder is highly critical because this determines the thickness of water held against the cylinder surface. It is difficult to set the tip really close to the cylinder because allowance must be made for uneven thermal expansion and dryer eccentricity; one way to overcome this, it is claimed, is to cut a groove into the inner surface of the cylinder opposite the siphon tip and allow the tip to run in the groove, but this necessitates thicker cylinders and is therefore expensive. For these reasons, on many modern high-speed machines a rotating siphon with the tip clamped to the surface of the cylinder and joined to a special rotary joint has been introduced. The advantage of this type of siphon, apart from being mechanically simpler to design, is that the layer of rimming water can be kept much thinner: Cooke (9) found that a rotating siphon could keep the layer less than $\frac{1}{32}$ in. thick, and this was much better than several models of stationary siphon (including the Cowie scraper type) for speeds between 1,000 and 2,000 feet per minute. It was also observed that a rotating siphon gave a much more stable load on the drying cylinder drive. Calkins (122) compared the performance of a rotary siphon set at $\frac{1}{4}$ in. and at $\frac{1}{16}$ in. from the inner surface and found the latter superior at speeds from 1,500 to 3,000 feet per minute and over a range of condensing rates.

It was formerly thought that under comparable conditions the rotating siphon required a greater pressure differential to ensure removal of the condensate than with the stationary type; this is because centrifugal force acting on the water must be overcome to draw it from the cylinder surface

to the axis, and this force increases with the speed of rotation (see for example, reference 100). However, Wahlström and Larsson (109) have shown that under normal high-speed operating conditions there is little to choose in this respect between the two types of siphon. The reason for this is that above 5 per cent. to 10 per cent. blow-through steam the frictional pressure loss in the siphon and condensate piping predominates over other losses of pressure across a drying cylinder, and is actually higher for a stationary siphon. Only for a very low blow-through does the reverse apply, i.e. the pressure differential required for evacuation under similar
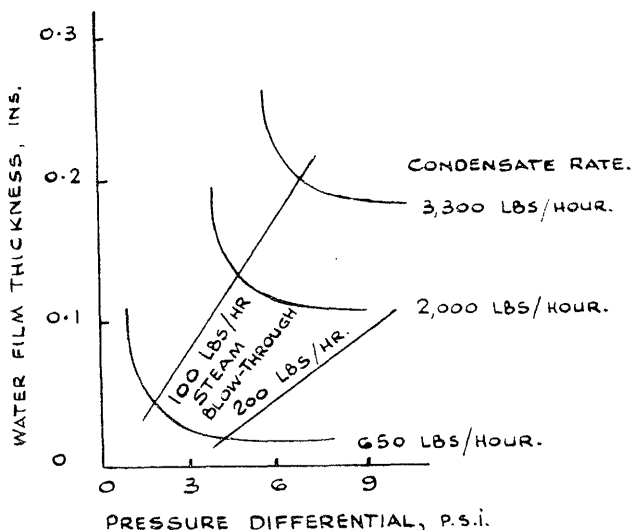
Fig. 5.24. Dependence of water film thickness on pressure differential in a cylinder revolving at 2,000 feet per minute, with a ¾ in. rotating siphon, for various condensing rates and amounts of steam blow-through (after Wahlström and Larsson)

conditions is greater for a rotating siphon. For such conditions of low blow-through the idea of having a suitably-sized hole in the side of the rotating siphon pipe to add slightly to the amount of steam blowing through, as reported by Daane (44), will aid efficient evacuation and reduce the chance of flooding because the siphon can still function with the tip covered by condensate. Nevertheless with a rotating siphon a considerable amount of blow-through must still be maintained during break conditions: this as a rule requires separate condensers that are connected in at such times and represent a significant addition to steam costs.

The actual thickness of the water layer when a cylinder with a rotating siphon is in rimming condition has been found by Wahlström and Larsson to depend on many factors. For instance, Fig. 5.24 depicting their results for a ¾ in. rotating siphon illustrates how the water layer thickness varies according to the condensing rate and the proportion of blow-through

450

steam under different pressure differentials. Above a certain amount of blow-through steam the thickness of the water layer is relatively independent of external conditions; but at lower levels of blow-through the layer thickness can rise rapidly and unstable conditions will ensue possibly causing the cylinder to flood. Thus, for efficient operation of a rotating siphon, particularly in conditions where the condensing rate can change relatively quickly, it is most important to keep the pressure differential well above the minimum theoretically required in order to ensure sufficient blow-through to retain the water layer at a stable thickness. It is for this reason that rotating siphons need to be operated at a higher pressure differential than stationary siphons, and the latter may be preferable even at quite high speeds well within the rimming region when limitations to the available steam pressure for drying are of over-riding importance.

The performance of rotating siphons also depends closely on the design, in particular the size of the tip and diameter of the siphon pipe; if too large the blow-through steam will in practice be reduced by using an orifice or valve in the condensate line, and this could bring the operating condition closer to the danger point if fairly wide variations in the condensing rate occur. To size correctly the dimensions of rotating siphons, the characteristics of both the siphon and condensate piping, and the condensing rate of the cylinder, need to be known in some detail; stationary siphons, on the other hand, always remove more water if the layer thickness increases, and so do not suffer from the same sort of instability—a wider margin for error is thus available.

A further disadvantage of the rotating siphon is that should cascading occur and a pool of water form in any particular cylinder due to a reduction in speed or to the volume of condensate present, then removal can become very erratic (26). Thus, apart from other considerations it appears that rotating siphons are only really advisable when machine speeds are high enough to make the rimming condition a reasonable certainty, and also when sufficient steam pressure is available to permit relatively high pressure differentials across each bank of cylinders. Future developments may lead to the adoption of a combination of stationary siphon and a scoop or rotating siphon arrangement, since according to Simmons (131) this possesses the advantages of both types and requires a negligible pressure differential to operate even at very high speeds. Another proposal by this worker is to use a drying cylinder with a concentric inner cylinder from which condensate is sucked by rotating siphons into the inner cylinder where it is removed by a stationary siphon. Rimming conditions are maintained in the outer annulus while the presence of a pool in the inner cylinder does not affect the efficiency of heat transmission.

5B. 3 3 Evenness of heat transmission across the cylinders

It is obviously important that both the flow of heat through the thickness of a drying cylinder and the resultant temperature at the surface are as even as possible across the machine. This can only be achieved in the first place if condensation occurs evenly across the inner surface of the cylinder, which implies a thorough diffusion of steam within the cylinder and an even

distribution of water across the machine at each point on the circumference.

Little investigation has been carried out to check how quickly and evenly steam actually does spread along the surface of a drying cylinder when injection takes place through the journal (always nowadays at the back side). On very wide machines, where difference in heat transmission at different positions across the cylinders becomes more prominent, some advantage has been claimed (89) in removing condensate at the opposite side of the dryer to the one where the steam is injected (in a modern version of the method still in use on some very old machines). For M.G. cylinders, spraying the steam from a pipe across the dryer axis, removing condensate from siphons at both sides, and cutting grooves in the inner surface to collect the condensate are all reputed to be helpful as well as in some cases giving an increase in the overall rate of heat transfer.

With the old scoop arrangement it is evident that water has to flow from the front side to the back (where the scoop is located), which means that the pool will be slightly deeper at the front side and drying on average slower at that side. This also applies to the stationary and rotating siphons, and Calkins (122) has demonstrated that location of the tip at one end of a cylinder causes a slight but definite difference in heat transfer across the width of the dryer which could be significant when cumulated through the whole drying section. With rotary siphons it is easier, especially at higher speeds, to arrange for the tip to be located towards the middle of the cylinder, which must give an improvement in this respect. But in this case there may be a tendency for the condensate to build up rather more near the edges of the cylinder, giving a slower rate of drying than the middle; however, this could be advantageous on most machines because, as seen in **5B.4 1**, ventilation conditions are generally such as to make it very difficult to prevent the edges of the sheet evaporating water at a faster rate than the middle.

These conjectures leave aside the important fact that however even the transmission of heat may be across the majority of the face of a cylinder, conditions at the extreme edges must always be different both by virtue of there being no paper to absorb the heat and also because some heat must be conducted through the sides of the cylinder. Loss of heat for the latter reason is small on fully-hooded machines and otherwise is minimized by such steps as covering the cylinder sides with aluminium paint to reduce radiation, but overcoming the change in conditions caused by the discontinuity at the edge of the web is a more difficult matter.

The presence of uneven heat distribution has been demonstrated by Campbell and Hughson (43) who measured the surface temperature across the dryers of an 1,800 feet per minute machine. They reported that this became higher towards the edges of the web, particularly the front, at a distance extending between one and two feet from each edge; outside the edge of the paper the temperature was even higher. The reason for this higher surface temperature at the edges of the paper was considered to be either that the condensate rim does not extend to the side of the dryer, or that steam scours out the sides giving better heat transmission. In the author's opinion, it is not necessary to postulate that conditions near the

sides inside the dryer are appreciably different. At the extreme edge, where there is no paper to receive heat, the flow must be much lower and for this reason alone the outer surface temperature may be expected to rise, in just the same way that the whole dryer temperature rises at a break if the same steam pressure is maintained inside the dryer. The higher temperature at the extreme edges outside the web will in turn raise the temperature in the adjacent surface regions of the cylinder; this, together with the lower heat demand at the edges of the paper due to more efficient ventilation, is probably sufficient to cause the surface temperature also to be higher for a short distance within the edge of the paper.

The outer edges of the paper made on the machine investigated by Campbell and Hughson were normally very dry at the reel-up, and if the flow of heat through the cylinders could be reduced near the sides it appeared likely that this condition would be remedied. It was therefore decided to study the effect of insulating the inside surface and a 9 inch wide brick lining was built in at both sides of one of the dryers. This reduced surface temperature at the sides successfully, and when seven drying cylinders had been treated in the same way the moisture profile at the dry-end was completely changed and the dry edges actually became damper than the rest of the web.

The result of this and other attempts to level up the rate of drying across the machine are valuable as an illustration of what can be done, though except for correcting gross differences this method, apart from practical difficulties, is probably too inflexible for general application particularly on machines making a variety of grades because alterations can obviously only be done with the machine shut. Certainly it must involve very careful experiment over a long period, together with an efficient means of assessing the changes in average moisture profile before a satisfactory compromise can be achieved.

Other attempts to overcome the edge condition have included inserting condensate-retaining rings round the circumference to increase the layer of water at the edges, and insulating the cylinder with asbestos at the edges. These appear to give similar results to those obtained with the brick lining, but such methods are still suitable only for a rough, general correction of gross differences at the edges.

Research into steam injection and condensate removal systems should eventually help to even out the conduction of heat across drying cylinders, but the edge problem is likely to remain less tractable. On existing machines, obtaining surface temperature profiles of drying cylinders is a useful exercise; though requiring some care to execute, it is probable that a sustained programme of checking in this way could show up defects in individual cylinders due, for example, to such things as the uneven deposition of rust which would produce cooler spots at different points across the cylinder.

5B.4 VENTILATION

Adequate ventilation of the drying section is important for the effect it has both on the overall drying rate and efficiency, and on the evenness of

drying across the web. In a larger context ventilation of the machine house as a whole is also important, particularly from the point of view of giving comfortable working conditions and preventing condensation.

5B.4 1 Ventilation of the cylinder pockets

Evaporation of water from the paper web occurs in the free draw between each cylinder; in fact, as will be seen later, there is considerable evidence to show that at higher machine speeds a greater quantity of water is removed in this way than by vaporization on the drying cylinders. In the constant-rate region of drying where the web is saturated at its surfaces in the open draw, the rate of evaporation (as discussed earlier) depends to a close extent on the condition of the air in the immediate vicinity of the web. In particular, the drier the air and the greater its velocity close to the web, the faster will be the evaporation. In the falling-rate region evaporation still occurs in the free draw, though conditions are less critical.

If the drying section were operated without any ventilation of the cylinder pockets whatsoever, the air in these regions would become largely stagnant and quickly rise in humidity until little moisture could be absorbed from the paper passing through in the draw. The only circulation would come from the natural rise in temperature of the air as a result of radiation and convection of heat from the cylinders; this would induce saturated air to leak out of the sides of the machine and be replaced by air from the machine house entering the pockets at a lower level. Apart from the fact that under such conditions the upper part of the drying section would be shrouded in steam and condensation would become a serious problem, the drying rate would be prohibitively slow and completely uncontrollable.

An early improvement on this situation was brought about by the introduction of various types of air extraction equipment. A familiar form involves a perforated tube extending across the width of the cylinders and connected to a manifold at the back side of the machine to which vacuum is applied. Condensation drains are provided on each extractor and sufficient insuction of air is created to keep the pockets as free from steam as possible. As with all pocket ventilation systems, a greater air flow is usually required in the early dryers where more moisture has to be removed.

This system has two important disadvantages. Firstly, it is cumbersome, taking up a lot of room in pockets which are already cluttered with felt rolls and cylinder doctors, and making removal of broke jammed in the cylinders more awkward. Secondly, the saturated air removed by each extractor is made up by air drawn into the pockets from the machine house; any fluctuation in ambient air conditions created by opening doors, altering drying on a second machine in the same building, and so forth is therefore liable to alter the drying rate. Furthermore, air entering pockets in the early dryers, which needs to be as dry as possible in order to remove the greater quantities of moisture evaporated from the damp web, is more likely to have come from the wet-end part of the machine house and consequently be already very damp.

A further aspect of this type of ventilation is that air entering at the side

454

of the machine picks up moisture as it travels inwards; thus, air in the pockets at the centre line of the machine tends to be at a higher humidity and therefore absorbs less moisture from the web (though this will in fact be partially corrected as the web progresses down the dryers because the paper temperature will rise in regions where evaporation is least, thereby increasing the drying rate and tending to even up moisture content across the web). This lack of uniformity in evaporation rate due to inflow of air from the sides of the machine is in fact common to most ventilation systems and is probably the main cause of the tendency affecting all machines to a greater or lesser extent for the moisture profile at the reel-up to be drier towards the reel edges. At the extreme edges of the web, the increased heat flow through the cylinders increases the dryness even further, as discussed in the previous section, though that particular effect is confined to a much narrower region than the hump in moisture content across the reel resulting from ventilation deficiencies.

The tendency to dry edges is frequently kept within tolerable limits only by increasing substance slightly from the middle towards the edges and by over-cambering the presses (or, more likely, by running a lighter load on the presses than the camber is designed for); both these actions make the paper damper at the edges when entering the dryers and thus compensate to some extent for the faster drying rate associated with that part of the web, but differences in characterisitcs of the paper across the machine at the reel-up and difficulties in running the press smoothly are inevitable consequences.

Some allowance for the higher drying at the edges can be made by altering the design of the extractor tubes so that more air is drawn from the pockets opposite the centre of the dryers. Likewise, some allowance can be made on individual machines for the fact that drying tends to be faster on one edge compared to the other, a situation frequently encountered which is caused by the masking effect on air flow of gears and other obstructions at the back side of the machine, and also by air being at a different temperature and humidity at one side of the machine compared to the other as a result of the layout and air flow in the machine house. The difficulty with improving the moisture profile at the reel-up by this form of compensation is that it requires an extremely lengthy process to achieve anything but a rough improvement; also any change made to the drying profile in this way is limited in extent and must be suitable for all grades of paper run on the machine.

A different approach to ventilating cylinder pockets is to induce turbulence and promote evaporation of water from web and felts by blowing in dry, hot air; the equipment takes the form of a perforated tube similar to that discussed above except that instead of sucking out the saturated air from the cylinder pockets fresh air is blown in, (this system should be distinguished from the use of special felt rolls to blow through hot air—these are dealt with under the heading of felt-drying equipment in **5B**.2 4). This permits closer control of the drying conditions than is possible when air is extracted and replaced from the machine house because the temperature and pressure of the supply air is readily varied.

Also, by supplying heat to the air in the cylinder pockets, less heat is drawn from the paper as the water evaporates; this is responsible for the appreciable rise in the drying rate that is usually found when this form of ventilation system is first installed. Many different designs have been devised but the most popular involve tubes stretching across the machine from which air is blown through holes or through jets sunk at intervals in the body of the tube to avoid protrusions on the surface. In common with the extraction system, this also has the disadvantage that the tubes are a nuisance in the crowded cylinder pockets, and as speeds have increased it has become more important to keep the pockets clear making it easier to remove broke and prevent it jamming in the cylinders.

This particular difficulty has been overcome in the Grewin system where air is blown across the machine from nozzles situated at both sides. Flexible connections to the supply manifold are comparatively simple to fix along the machine frame and a normal arrangement involves blowing air alternately from opposite directions into successive pockets. A greater volume of air is required early in the drying section and two nozzles may be fixed in each pocket, one below and one above the felt roll, blowing in opposite directions. The volume of air blown into different pockets may be regulated by the nozzle opening (adjustment of these may also be used for compensation when drying is greater at one side compared to the other), and the supply air is controllable with respect to pressure and temperature. The pressure is normally set high enough to be able to feel air being pushed out at the opposite side, but not so high as to set up flapping at the sheet; since air issues from the nozzles in a narrow jet which gradually widens out, at normal supply pressures the effect of any individual nozzle is usually greater at the opposite side of the machine.

Temperature of the air is set at a level which is economically sound and must be determined by experimentation and measurement of the total heat consumption under different conditions. If the temperature is too low, the web is allowed to cool too much in the free draws as water is evaporated from it and the only improvement in the drying rate comes from the improved circulation of air in the pockets; if too high the sheet could actually heat up in the free draw, reducing the heat flow from the cylinders, and this is liable to be inefficient because losses will be much greater—also the paper surface is likely to be affected if its temperature rises too high. Normally the temperature is in the region of 200 deg. F. to 300 deg. F.

The Grewin system has been widely adopted because of the ease of its installation on existing machines and the obvious improvement in drying rate that it generally creates, particularly of course when ventilation had previously been rudimentary. Especially where drying is limited by the steam pressure available, such an installation is valuable as it can bring about a reduction by several p.s.i. in the pressure necessary to sustain production. Some improvement in the moisture profile at the reel-up is also usual, though from the nature of the air flow set up by the nozzles it cannot be expected that dry edges are overcome.

A more recent ventilation system which can be used with particular advantage in the early dryers incorporates a method of blowing hot air

through the cylinder doctors. This avoids the awkwardness of having a special tube and, especially if means of adjustment of the flow near the edges of the sheet is available, this method of supplying air to cylinder pockets appears very promising. Ideally, to obtain true cross-web uniformity of ventilation it will obviously be desirable not only to inject hot air evenly across the width of the cylinder pockets, but also to extract it evenly. The use of such doctors together with suitable full-width extraction equipment, possibly utilizing suction in specially-designed felt rolls, could achieve this end especially where open-weave fabric dry felts allow easy passage of air through the felt.

5B.42 Removing the saturated air; hoods

Whatever the system of ventilation in cylinder pockets, a large volume of saturated air is invariably expelled out of the sides of the machine and rises by virtue of its high temperature. Some means of evacuating this moisture-laden air is essential. Older machines may be covered by no more than the natural roof of the building, with two or three vents to allow the steam to escape; in many cases a false roof is constructed over the machine. Natural ventilation of the machine in this way is uneconomical and too uncontrollable for modern machines and the usual method of improvement lies in provision of a hood with appropriate air exhaust and supply fans.

A variety of hoods are available and depend for their construction on the lay-out of the drying section, the drive, existence of a basement, and so on. It is normally possible to walk alongside the dryers within the hood and large access doors are available at intervals for entering and for removing broke. An essential feature of all types of hood which cover the sides of the machine is quick and generally automatic raising of the panels to permit rapid attention in the event of a break. This applies also to covers placed over the ends of the hood where paper is fed into and out of the dryers. Material is commonly either asbestos board or aluminium panels which are light, reasonably cheap, and give a good insulation. Air is withdrawn from the hood at two or three points along the dryers by means of exhaust fans and there is frequently provision of some heat-exchange arrangement for warming fresh air and water.

The simpler 'open' type of hood may take the form of a straightforward canopy over the top of the machine with side panels extending only about as far down as the journals of the top cylinders; retraction gear is not usually necessary in this case and normally there would be provision in the hood only for exhaust fans (which could be speed-controlled from the humidity of the exhaust air using a dew-point measurement), the air being supplied partly by a Grewin or other pocket ventilation system and partly from machine house fans.

'Closed' hoods may have covers extending to the machine-room floor and into the basement; with this type it is usual to balance exhaust and supply air within the hood itself, leaving only a small volume to be drawn in from the machine house. The supply air can go to Grewin nozzles, to air

blowers directed on to felts (especially bottom), to slots discharging low-velocity air along the lower edge of the hood ('air curtain'), and to other places within the hood; the air is usually temperature and humidity controlled.

Elaborate instrumentation is frequently associated with closed hoods with the object of reducing heat consumption to a minimum and keeping drying as consistent as possible irrespective of ambient air conditions both inside and outside the building. The controls adopted depend essentially on the design of the hood and position of the fans and recirculation system. As an example: the speed of the exhaust fans can be regulated to keep the humidity of air drawn from the hood constant, the speed of the supply fans being adjusted simultaneously to maintain the overall balance; the quantity of air recirculated to the supply fan can be controlled to keep the humidity of the supply air at a suitable value; and the dry-bulb temperature of the supply air can be controlled (by admitting more or less steam additional to the heat exchanger) at a set-point which can be altered to suit conditions. With such a comprehensive system it is possible to maintain drying steady for long periods though simpler systems, for example using only a damper to control manually the recirculation of exhaust air according to a measurement of its humidity, are probably sufficient in many cases.

Where hoods have been installed on existing machines substantial improvements have been claimed (for example, see references 5, 6, 8 and 10). Drying is often found to be more uniform across the sheet, though this may be attributed more to the fact that when a hood is installed some system of supplying hot air to the dryers is generally put in at the same time. The life of felts over the early dryers is likely to improve due to the overall drier conditions in the pockets and to lower running moisture in the felts, while working conditions in the machine house will also be much improved. But above all the specific steam consumption (as shown by relating the total steam consumption to the water removed from the paper) is certain to improve even with a simple open-type hood; it is frequently the case, however, that no noticeable change occurs in the actual evaporation rate. When the hood is closed further economies are effected because the supply air can be made much drier than air in the machine house, thus reducing the volume of air which must be handled for a given rate of moisture pick-up.

With any hood heat-exchange equipment in the exhaust air is very important if the full potential of the hood is to be realized. For instance, Chalmers (8) has compared steam consumption on three machines making the same grade of paper as follows: 6,200 lbs. steam/ton paper on a machine with an open-type canopy hood and 3 exhaust fans but no heat-exchange equipment; 5,780 lbs. steam/ton on a machine with similar hood but equipped with four single-pass economizer units; and 5,450 lbs. steam/ton on a machine with totally enclosed hood and double-pass economizer units. Even with heat-exchange equipment the steam used for heating the supply air may represent over a quarter of the total consumed in the drying section so it is important to experiment with different settings of

the supply air humidity and temperature, the exhaust humidity, etc., in order to get some idea of optimum operating conditions. Fortunately it appears often to be the case that quite large variations in running conditions can be made, for example by varying the volume of recirculated air or the temperature of the supply air, without affecting markedly either the overall steam consumption to dry the paper to a given moisture content or the moisture profile at the reel-up (5, 6).

 Hoods over M.G. cylinders are basically similar to those over multi-cylinder drying sections though design of the hood to prevent stagnant regions and stratification of air in different places across the machine is much more critical. According to Knowles *et al.* (17), it is necessary to keep the supply air volume much lower than the exhaust in order to give a large leakage of air into the hood. The purpose of this is to prevent a layer of air next to the paper (measured at up to 3 in. thick) from moving with very low velocity relative to the paper and thus rapidly becoming saturated; the disadvantage of having a large insuction is that air tends to be drawn in mainly from the wet-end of the hood where it is already at a high humidity. When exhaust air is recirculated to the supply line, it is taken preferentially from the dry-end of the hood. With most ordinary types of hood on M.G. cylinders it appears frequently to be difficult to get an even distribution of drying across the sheet and recent years have seen the high-velocity-air hoods, described in 5B.5, becoming increasingly popular for this particular application.

5B.4 3 Ventilation of the machine house

On machines without any form of hood, the ventilation system of the machine house has an important influence on the drying because it governs the condition of air circulating into the cylinder pockets. Even when some system of forced ventilation of heated air into cylinder pockets is used, a large proportion of the volume of saturated air leaving the pockets must normally be replaced by machine house air. This also applies to open-type hoods and only a totally-enclosed hood with a balanced exhaust and supply air system can be expected to function independently of the machine house air circulation.

 It is important for these reasons that the machine house should be supplied with air by fans at a rate approximately equal to that at which it is extracted. Otherwise, air will enter or leave the building wherever it can, making the condition of the air and the drying sensitive to open doors and windows. Most mills seem to operate with the volume of supply air somewhat lower than the exhaust air volume, but unless the machine is well hooded the possibility of variable draughts affecting drying cannot be discounted. On machines making grades of paper which require a high degree of cleanliness, such as photographic base, ingoing air is well filtered and the volume kept slightly greater than the exhaust to maintain a slight pressure in the building.

 Apart from equalling up the volume of air entering and leaving the building, it is necessary to regulate the condition of the air blown into the machine house if the effect of varying atmospheric conditions is to be

reduced. In this country climatic variations are relatively mild and normal procedure is to heat air entering the building in winter and accept its natural condition in summer. But this is done primarily to avoid condensation and is often not subject to any close control. In colder climates with more extreme conditions the effect of variations in temperature of the air entering the building become more evident and it is more common to apply a strict temperature control through heaters at the supply fans. In addition thermal insulation of the building is more carefully considered in order to reduce natural heat losses. Where the climate is humid (and this really applies to this country for a lot of the year), and particularly where it is also hot, it may be economically worthwhile to cool air entering the machine house in order to condense out moisture; by increasing the quantity of water that can be comfortably picked up by the air it then becomes possible to reduce the volume handled, and hence the power costs. Unless a machine is fully hooded the exhaust-air volume may have to be increased in summer to keep working conditions tolerable.

The choice of positions at which air is blown into the machine house is equally as important as the condition of the air. This requires study by a ventilation engineer if adequate circulation through the whole building is to be achieved, particularly at the wet-end where working conditions can easily become unpleasant when stock is heated. Currents of air need to be steady, and planned to clear the hottest places; such things as changes in humidity round the dryers caused by surges of damp air from the wet-end into the aisle or down the back side of the machine must be avoided. Condensation of hot, humid air contacting cold surfaces can be a problem, especially where drips fall from the roof and girders on to the web and cause slugs in the paper. With the adoption of closed hoods and the trend towards reducing the amount of exposed surface at the wet-end, this nuisance is becoming less troublesome nowadays; nevertheless it is now common practice to counteract condensation by heating the false roof. The whole arrangement and siting of fans, and control of the incoming air condition, needs comprehensive design to cover the extremes of atmospheric temperature and humidity which occur throughout the year. It may even be desirable to vary the position of fans used at different times of the year, for example by blowing down to machine-floor level in summer and up to the roof in winter.

The necessity of heating air entering the machine house at various places raises the question of how this is to be done. More and more mills are taking steps to recover as much as possible of the heat leaving the building in the exhaust air, and in closed-hood installations this is generally considered as an essential step for the full potential of the hood to be gained. As much as 40 per cent. of excess heat in the exhaust air from a hood can be recovered by this means. The simplest type of heat-exchange equipment utilizes the exhaust air to heat air entering the hood and machine house. More elaborate equipment like the Ross-Briner Economizer involves a double-pass system which first heats air up to 150 deg. to 200 deg. F. for passing to felt-blowing nozzles and other parts of a hood, then in a second exchanger heats air entering the machine house. Another arrangement

which is becoming increasingly common is to spray fresh or whitewater into the exhaust air and in that way to recover heat for use in water supplies to felt sprays, vacuum pump seals, flash steam condensation, and to other parts of the mill. Supply air to Grewin nozzles is normally drawn in the first instance from the machine house or the false roof and heated separately by steam under temperature control.

Recovery of heat in exchangers naturally varies with the season; in summer, heating of supply air to the machine house would be turned off, while in winter additional heating may be required as well. But over the whole year the economic benefit of heat-exchange equipment is obvious and installation of one or other type may be expected soon to be regarded as an integral and indispensable part of the paper machine.

5B.5 AUXILIARY DRYING METHODS

The use of steam-drying cylinders is the basic method of removing water from the paper web, but apart from this there are other means of drying which are frequently utilized in an auxiliary capacity. These are usually adopted to increase evaporation rate on a machine where the dryers are limiting production, or to shorten the drying section of a new machine; also in some cases the auxiliary system permits differential drying across the web and can thus be used as a means of correcting the reel-up moisture profile. The high-velocity-air hood is the most important device falling into this category; in fact, the use of this type of hood may now be considered almost an integral part of an M.G. cylinder arrangement, though application has spread extensively to multi-cylinder drying sections.

5B.5 1 High-velocity-air hoods; general comments

High-velocity-air hoods, or H.V. hoods, were first installed towards the end of the 1950s. Despite their relative newness there have been a tremendous volume of reports put out about their operation and performance, and hard competition to enter a new field has led to an unusual degree of acrimonious discussion, claims and counter-claims. An attempt will be made in what follows to assess the situation with as much care as possible.

Mention has already been made of the unevenness in drying which frequently occurs when using an ordinary type of hood over an M.G. cylinder. This is due largely to stagnant regions in the hood and to the tendency of the paper to carry a moisture-laden layer of air along with it over the M.G. cylinder. H.V. hoods were first developed to overcome these disadvantages by projecting hot air at high pressure directly on to the paper over the whole of the hood. Nozzles carrying the air are placed very close to the paper, and after taking up moisture the air is extracted as evenly as possible over the whole hood area from in between the nozzles; fans supply air through a heating system at the appropriate velocity, temperature and humidity, and also extract it. A H.V. hood over an M.G. cylinder is usually divided round the circumference of the cylinder into a number of self-contained compartments, though the exhaust from one may be fed to the supply of the next compartment round the cylinder. It is

largely in the design field—the arrangement and shape of nozzles and extraction area, the size of heaters for the supply air, the velocity-range of the fans, and so on—that there has been much discussion, but also there are differences of opinion as to where H.V. hoods should be located on a multi-cylinder machine. Before going into these points in more detail, it is appropriate first to make a few general comments on H.V. hoods.

The main purpose of projecting air at high velocity on to the paper surface is to keep the layer adjacent to the paper as dry as possible, thus promoting the evaporation rate; the volume of air passing through the nozzles must be sufficient to create even conditions across the machine and remove all the moisture picked up. Heating the air serves the twofold purpose of reducing its humidity and keeping the high heat losses in the paper caused by rapid evaporation to a minimum.

For multi-cylinder drying the advantages compared to using conventional dry felts are primarily reduced resistance to transfer of vapour from the web and lowered heat loss from the outer surface. The main disadvantage is that the closeness of contact between the web and cylinder which is promoted by a felt is lost (although the pressure of the air jets will to some extent reduce the deficiency); this increases heat transfer resistance from cylinder to paper and in some applications the consequent drop in heat flow may outweigh any gain in evaporation rate brought about by the hood. Gardner (101) has proposed the use of a soft pressure roll, similar to that used on M.G. cylinders but employing relatively low nip pressures, in order to improve contact between web and cylinder before passing under the H.V. hood; this would also have the advantage of reducing trouble caused by air becoming entrained between the web and cylinder, a nuisance which becomes more common as speeds increase until apparently a point is reached when there is a complete air film that effectively insulates the web from the cylinder and makes it sensitive to small pressure variations on the surface.

Poor contact between web and cylinder may also be overcome by the use of plastic fabric felts in conjunction with H.V. hoods, a combination which largely retains the individual advantages of both provided the felt is sufficiently open not to interfere with the air jets, yet does not mark the sheet. Another advantage of fabric felts is that their use overcomes guiding difficulties which usually occur when several H.V. hoods are used over successive cylinders. Unfortunately operational reports of this technique are still scanty.

In the normal H.V. hood application certain practical difficulties must be overcome. The clearance between the nozzles and paper is very small and if a break occurs the hood must be rapidly retractable to between one and two feet from the cylinder. This applies particularly to hoods on bottom cylinders where broke will easily jam up in the hood and foul the fans. Retraction is generally automatic at a break, and at the same time the fans and heat supply may either be automatically stopped, or reduced in output to keep air in the hood at a constant temperature. Any tendency for paper to be sucked into the exhaust fan at a break must be reduced by careful design of the extraction unit; a useful arrangement in one type of H.V.

hood (Spooner), which makes it easier to clean and to clear broke should any get sucked into the hood, is to have a reversible axial-flow extraction fan. Ropes are used for feeding up and the hood is normally lowered only when the full width of sheet is over the cylinder.

Installing a H.V. hood on an existing machine is generally a complex task due to the bulk of the hood itself and the crowded conditions which characterize conventional drying sections. Felt runs round adjacent dryers have to be modified and to ensure a reasonable wrap of hood it is usually preferable to alter cylinder spacing. The volume of steam condensed in a dryer under a new H.V. hood can be substantially higher than formerly, with a consequent risk of flooding; for this reason it is advisable also to install individual pressure gauges and valves on any drying cylinder covered by a hood.

There have been several reports of damage to the paper surface caused by H.V. hoods. Small slugholes, in which a flap of paper is folded back from the hole, are caused by the movement under the high-pressure air jets of pieces of heavy dirt embedded in the paper; dirt carried in the air itself can produce the same effect, which makes it advisable to filter fresh air drawn into the hood to a reasonably fine degree. Another fault which is sometimes observed on M.G. applications, particularly at the edges, appears in the form of damp patches in the paper which if large enough may show tendencies to cockle. These are caused when certain regions of the paper are sucked off the cylinder surface (a result basically of poor design of the hood); in extreme cases there may be repeated breaks due to this and the trouble can be overcome only by increasing tension in the paper or decreasing the air velocity.

Apart from these operational defects, the quality of paper appears to be little changed when passing under H.V. hoods. Brauns and Larsson (69) have reported indications that some loss of smoothness can occur with H.V. hoods applied to a multi-cylinder drying section, especially where the entering moisture content is between about 40 per cent. to 20 per cent.; also some increase in cross-machine shrinkage of a greaseproof paper was observed when moisture content entering a H.V. hood was lower than 35 per cent., though for other types of paper no change in shrinkage was detected. Jepson (90) considers that H.V. hoods over early dryers can reduce tendencies towards cockling (this is likely if the original source of cockling was primarily due to felt unevenness, though even if cockling originates largely from substance variation the drying rate with high-velocity-air may be less sensitive to the varying quantities of water to be evaporated and reduce cockling in this way). On the other hand, where hoods have been applied to only one side of the web, and especially when this has been towards the end of the drying section, it has been noticed that curl is induced in the paper; this could, however, be turned to advantage on some machines where differential H.V. hood drying on top and bottom cylinders could offer a means of curl control less difficult to arrange than applying differential steam pressure to the cylinders.

Several designs of H.V. hoods are compartmented at intervals of 12 in. to 15 in. in order to permit the nozzle air velocity to be varied, usually by

adjustment of a damper. Harrison (60), Kerler (91), and Mercer (95) have described installations of H.V. hoods with this facility (in each case the hood was sited about three-quarters down the drying section), and there is no doubt from the results presented that adjustment of the dampers enables an important improvement in the reel-up moisture profile to be achieved. It is not possible to control narrow moisture streaks very effectively and adjustment of moisture by alteration of one damper can often affect the moisture level in adjacent positions, but with careful use a much more even moisture profile can evidently be obtained. Some authors claim, however, that the moisture profile improves anyway when H.V. hoods are installed and imply that the refinement of being able to adjust operation across the width of the machine is not necessary or helpful; although the existing designs of damper arrangement are certainly not perfect, it would be surprising if the facility were not found economically beneficial on at least some machines.

A useful summary of the design and operational characteristics of ten different models of H.V. hood suitable for use on multi-cylinder machines has been given by Larsson (76).

5B.5 2 Design and operating conditions of H.V. hoods

There are many differences in design of the various makes of H.V. hood available on the market, and also in the conditions under which it is recommended that they operate. The primary design feature, and the one about which there has been most contention, is the shape and arrangement of the nozzles through which the air blows on to the web; in particular, should these be circular or slotted to give the best distribution and performance? Allied to this is the question: to be effective how near to the paper should the nozzles be placed? The optimum gap between nozzle and paper is dependent on the velocity of emission through the nozzles, and the choice of this is in turn affected by the condition of the air supplied to the nozzles.

One of the reasons for the differences of opinion existing amongst H.V. hood designers is that the mechanism of drying by this means is not clearly understood. Several workers have formulated theories, notably Jepson, Gardner, Allander, Hurm, and Daane and Han, but each differs in various respects from the others; a useful summary of their salient points has been given by Larsson (76).

Many of these authors have also reported the results of experimental work designed to simulate H.V. hood operation in various ways, usually with the object of determining conditions giving rise to the best transfer of heat from the air to the surface it impinges upon. These too have in many cases given contradictory results. For example Gardner (58), guided by his theoretical calculations, found the best performance of several different arrangements occurred when the nozzles were in the form of slots 0·75 mm. wide at 1 in. spacings. But Allander and Eneroth (81) compared the performance of both slots and round holes and arrived at the conclusion that holes are capable of giving 25 to 40 per cent. higher heat transfer and should also not be so sensitive to the gap between nozzle and paper.

Apart from the question of the actual shape of the nozzles, most authors are agreed that the greater the number of nozzles in a given area, the better is likely to be the uniformity of drying; however, the overall percentage open-area affects the volume of air needed to achieve a given velocity (and hence power costs), and must be kept low to avoid interference between jets. The minimum nozzle size has to be consistent with there being a negligible risk of blockage from dirt and fibre dust. The nozzle size is also governed by the width of the gap between the nozzles and paper: in general the narrower this gap can be set at within practical limitations (usually between $\frac{1}{2}$ in. and 2 in.), the smaller can be the nozzle size without reducing heat transfer efficiency, though different designs vary in the sensitivity of their performance to relative changes in these dimensions. A practical point of importance in this respect is that the gap can alter significantly as the system heats up and allowance may have to be made for this in the initial setting-up.

Most authors consider that heat transfer increases with increasing velocity of air through the nozzles, other conditions being constant, and that the jets should be directed perpendicular to the paper surface. But higher velocities demand increases in fan power proportional to the cube of the velocity, while according to Allander and Eneroth the heat transfer increases only proportional to speed raised to the power of 0·75. This implies that to double heat transfer by increasing air velocity would demand a 16 times increase in the power, yet it is calculated that this will yield only a 20 per cent. higher evaporation rate. In addition to this, increased velocities bring more risk of damage to the paper, particularly for low substances, and there are likely to be greater losses around the hood. In practice, the range of air velocities used in H.V. hoods is from 5,000 to 15,000 feet per minute.

The condition of the air supplied to the nozzles is primarily a matter of finding the most suitable temperature. If this is too low, the high velocity of the air will have a cooling effect on the paper surface which will inhibit evaporation. On the other hand, very high air temperature may bring about removal of moisture at a rate greater than can be diffused to the paper surface; the web then becomes so hot that there is a risk of surface hardening, and even blistering and burning of the upper layers may occur. In between these extremes there is agreement that increasing temperature produces better heat transfer, though higher temperatures demand greater steam consumption so economic considerations must be taken into account; on H.V. hoods with sectional cross-web control, it has also been reported that operation of the dampers becomes increasingly sensitive at high temperatures (95). Normal operating temperature is from 250 deg. F. to 450 deg. F., though some hoods employ temperatures up to 600 deg. F. Steam-heating is common, especially for hoods working at lower temperatures, though oil, gas burners and electric heating are also used.

There is normally some form of recirculation of air, with only a relatively low proportion of fresh make-up air admitted at a rate which can be controlled automatically to keep the humidity of the supply air at a desired level. Because this level closely affects running costs, it must be carefully

chosen to give the best compromise between the evaporation rate achieved and the overall heating costs (increasing the volume of make-up air will lower humidity, thus improving the evaporation rate, but at the expense of a higher heat demand). As an example of the effect of changing the percentage of make-up air, curves given by Jepson (36) are shown in Fig. 5.25. These indicate that for this particular hood increasing the proportion of make-up air above about 20 per cent. yields little improvement in evaporation rate, though the overall specific steam consumption of the H.V. hood and M.G. cylinder concerned shows a steady increase.

In some cases separate heaters are used, one to keep up the temperature of the recirculating air, the other to heat the make-up air. This is claimed
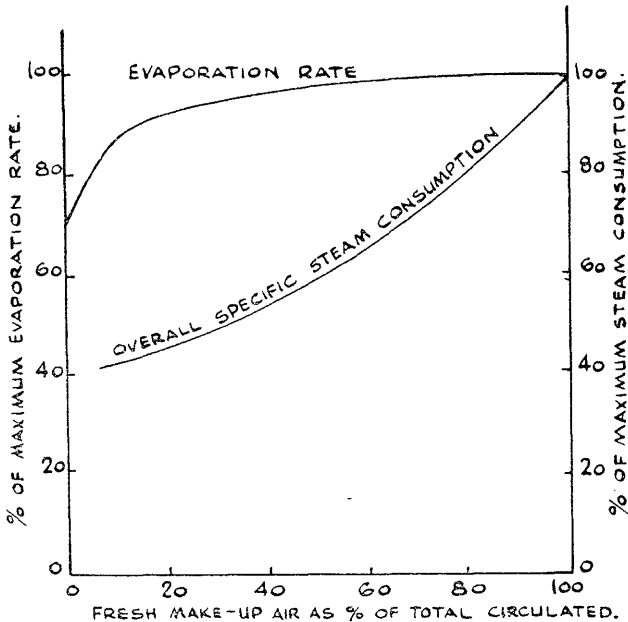
Fig. 5.25. Relation of evaporation rate and overall specific steam consumption of an M.G. cylinder and H.V. hood for varying proportions of fresh make-up air in the hood (after Jepson)

to allow more careful control under varying exhaust conditions. Exhaust air passing to atmosphere can be usefully passed through some form of heat exchanger, similar to those discussed in the section dealing with machine hoods.

With all these variables in the operation of a H.V. hood, it is extremely difficult to select between various designs and to know even approximately what the most suitable operating conditions are like to to be. Each installation requires careful individual study, with particular emphasis on the economic aspects and taking into account reductions in operating costs

which will occur if any felt dryers can be dispensed with, or if air heating associated with ordinary drying-section hoods is reduced. The capital cost of a H.V. hood may well be slightly higher than the number of ordinary drying cylinders it is equivalent to in terms of evaporation rate, while steam consumption may be fairly similar. Ideally, once installed a H.V. hood requires extensive testing under comparable conditions to determine the optimum running levels of air velocity, temperature and humidity in relation to overall heat and power consumption—a rather formidable proposition especially as the best conditions may well vary with the grade of paper being dried. This, of course, presupposes adequate instrumentation to control these air conditions, an important feature of any H.V. hood.

One final point must be mentioned. An important difference in operation distinguishes one particular make of hood (Greenbank) which simply heats up the saturated exhaust air and uses this for supplying the nozzles (67). Very little saturated air leaves the hood and replacement is from normal leakage into the hood at the sides; in effect, this hood uses superheated steam as the drying medium instead of air. This has allowed a more compact design to be achieved, with fans and heaters inside the hood and no bulky air ducts. At temperatures above 250 deg. F. it is claimed that the use of superheated steam gives a greater evaporation rate than air, and yet is cheaper to use under comparable conditions. This has been hotly contested by manufacturers of the conventional air-heated H.V. hoods, and an objective comparison of the two systems is still awaited.

5B.5 3 Installing H.V. hoods on multi-cylinder drying sections

When H.V. hoods are put on to existing multi-cylinder drying sections, their performance is apt to vary appreciably according to the conditions of installation, and the observed increase in drying capacity may be equivalent to as few as two, or as great as six or more individual dryers in the corresponding part of the drying section (69, 78, 90). Two or more hoods installed in series over top or bottom cylinders are not additive in effect, the second one has a much lower efficiency than the first while a third may have hardly any observable effect at all. This phenomenon is generally attributed to there being insufficient time available under extremely fast drying rates for moisture to migrate through the thickness of the web to the surface in sufficient quantity to maintain the same drying rate.

The most important question when installing a H.V. hood is: in what part of the drying section should it be placed? Many case histories of individual H.V. hood installations in all parts of the drying section describe improvements in performance which have occurred, but there are only two detailed accounts giving direct comparative data.

In the first of these, Brauns and Larsson (69) compared the performance of two H.V. hoods on the Swedish Central Laboratory experimental machine; one of these hoods was placed over a lower cylinder about two-thirds the way along the drying section and had hole-nozzles, the other was placed over the next upper cylinder and was equipped with nozzles in the form of slits. Various types of paper were run on the machine and the moisture content entering the first H.V. hood was varied from between

60 per cent. to 10 per cent.; temperature of air to the hoods was also varied systematically, but otherwise experimental conditions were kept as steady as possible. Sampling paper before and after each hood and testing for moisture content enabled the evaporation capacity of each hood to be determined.

Results obtained for kraft paper are shown in Fig. 5.26. These illustrate that the water evaporated diminished in both hoods as the moisture content entering the respective hoods decreased. This is to be expected since with decrease in moisture content there is less water remaining to be evaporated. Also shown in Fig. 5.26 is the corresponding evaporation for a felt-covered
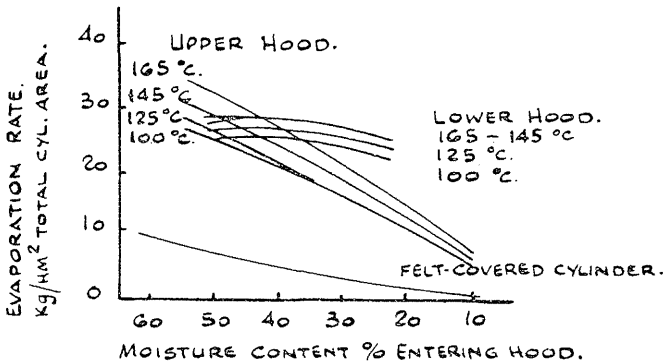
Fig. 5.26. Evaporation rate of two H.V. hoods at different air temperatures for varying moisture content entering the hood (after Brauns and Larsson)

cylinder. If the water evaporated using the H.V. hoods is compared with that for the felt-covered cylinder, the ratio between the two varies with moisture content entering the hoods as in Fig. 5.27. This illustrates that the hoods are comparatively more effective for a lower entering moisture content, in other words they should improve drying rate proportionally more towards the end of the drying section; similar results were obtained with newsprint. With greaseproof paper, although the evaporating capacity of the hoods declined with decreasing moisture content, as for kraft paper and newsprint, the water evaporated over a normal felt-covered cylinder declined much more slowly (characteristics of the paper having more influence on drying rate towards the end of the dryers). Because of this, the ratio between the H.V. hood and felt-covered cylinder keeps pretty much the same irrespective of entering moisture content, and for this grade of paper the position of the H.V. hood in the drying section would be less important from the point of view of obtaining maximum increase in drying rate.

The difference between the performance of the two hoods as shown in Fig. 5.26 deserves some comment. The lower hood gave a better per-formance than the upper, except at high entering moisture content when the reverse was the case. The reason for this is attributed to the fact that at

high moisture contents the lower hood acted partly as a means of heating up the web to the advantage of the upper hood which then followed; at lower moisture contents the more common effect of having two hoods in series explains the lower performance of the upper hood. Apart from this point it is not possible to draw any firm conclusions as to comparative performance of holes or slits because the hoods were not interchanged, though there is perhaps an indication that the performance of hole-nozzles is less dependent on the entering moisture content.

One further point about these results which should be noted is the effect of varying air temperature in the hood: this becomes of increasing importance at higher moisture contents. It may be expected therefore that
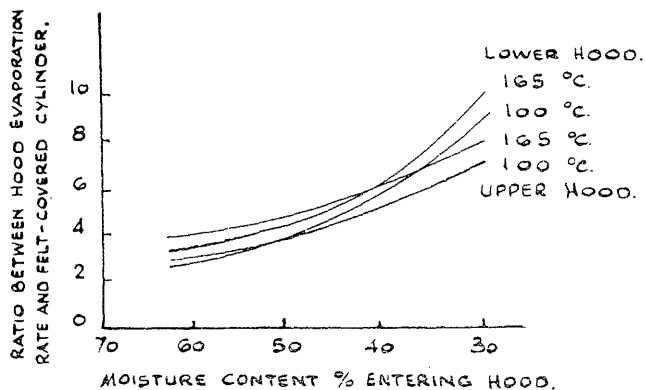
Fig. 5.27. Ratio between evaporation rate of two H.V. hoods and that of a felt-covered cylinder for varying moisture content entering the hood (after Brauns and Larsson)

towards the end of the dryers no advantage will accrue from having the air temperature higher than normal.

The other report presenting comparative results on using H.V. hoods in different parts of the drying section is due to Jepson (90), who cites observations made on a paper machine to which ten H.V. hoods were fitted over the top cylinders of a 21-cylinder drying section. The hoods were arranged in three separately controlled banks comprising 4, 3, and 3 hoods over individual cylinders. The speed which the machine could be run at (without felts and presumably at maximum available steam pressure) increased 15 per cent. with the first bank of hoods operating, 24 per cent. with the second bank alone, and 34 per cent. with the third bank alone; with all three hoods working the increase in speed was 55 per cent. In other words the hoods at the dry end of the dryers had a greater effect, other conditions being equal. It will be noted, as observed above, that the effect of using all the hoods together is not additive.

These two reports thus show quite strongly that H.V. hoods are likely, in general, to be more efficient in the later stages of drying. This need not always be the case, as for example with greaseproof paper, and the position

16   469

chosen for any particular application needs to be related to the drying curve of the paper; where this is comparatively slow over the early dryers a greater improvement may occur with a H.V. hood in that position. The reason for the greater efficiency of H.V. hoods when the sheet is comparatively dry is not absolutely clear, but it must be remembered that the basis of comparison is with felt-covered cylinders. Removal of a felt in the early stages of drying gives a bigger reduction in overall evaporation rate than removal in the falling-rate zone of drying where the conventional multi-cylinder section is less efficient. Also, installing a H.V. hood at the beginning of the drying section leaves the remaining dryers to operate in the less-efficient region. On both these counts, when substituted for felt-covered cylinders H.V. hoods are likely on a purely comparative basis to show greater improvement if installed towards the end of the dryers.

5B.5 4 Other auxiliary drying techniques

There are a number of other methods of assisting the drying process, of which the more important worth noting are infra-red drying and drying under vacuum.

The use of infra-red heating from oil or gas burners or electricity has been strongly advocated from time to time but does not seem to have caught on to any extent. Undoubtedly the main reasons for this are that the cost can be prohibitive, and there is often a fire hazard involved; further, there is no general agreement as to how efficient particular installations are likely to be nor where is the best position to put them in the drying section.

Bhargava and Robertson (39) have given a comprehensive review of the problems involved in using infra-red radiation, in particular of the need to select carefully the predominant wave-length of emission (which depends basically on the temperature of the source) in order to ensure maximum absorption by the web. These authors state that even with high-efficiency energy usage the cost of evaporating water from a paper web can be approximately twice that of steam (though this, of course, depends on relative fuel costs) though capital expenditure for an equivalent capacity is lower. Experimental work showed that heat is absorbed, and water evaporated, primarily in the surface layers facing the heater; the rate of evaporation is fairly constant irrespective of moisture content of the web, in comparison with drying cylinders where there is a steady decline. This suggests that infra-red radiation is more likely to be successful when used to augment the later stages of drying.

Other authors (for example, 75) agree that infra-red drying is best applied when moisture content of the paper is low, though some, including Burgess (57), consider that it could be applied more effectively to augment drying in the constant-rate period when moisture is present on the surface of the paper. Eisele (45) has conducted laboratory experiments which showed a decline in the effect of infra-red radiation at moisture contents lower than 25 per cent. to 30 per cent., thus contradicting those of Bhargava and Robertson; this worker also found that the results obtained using infra-red depended on several other factors such as thickness of the paper and exposure time. Prince *et al.* (64) is another author who believes that

infra-red should be applied before the drying section to obtain the best performance; he considers that the heating effect from an early infra-red application enables temperatures used in the first few dryers to be higher without the risk of picking or burning the web. It is evident from all this that at the present time the value of infra-red radiation as an auxiliary means of drying, and the best method of applying it to a paper machine, are by no means clear.

One possible application of infra-red drying is to allow correction of cross-web moisture irregularities by dividing the heater across the width of the machine into a number of individually controllable banks. For this purpose it is more likely that an installation will work efficiently if placed at or close to the end of the dryers. Incorporation of such an arrangement in a H.V. hood has also been considered.

Drying under vacuum is theoretically a sound idea because evaporation then occurs at lower temperatures. This either makes an appreciable increase in drying rate possible on any particular machine, or can approximately halve the number of cylinders needed to achieve a given rate of drying. The Minton Vacuum Dryer operates on this principle and involves placing all the dryers in a sealed hood to which vacuum of up to 28 inch Hg is applied; several successful applications have been described by Hill (46). Brightness of the paper is claimed to improve though there are difficulties in obtaining satisfactory sizing due to the prevailing low temperature of the web which may not exceed 100 deg. F. The main problems with this device lie in the need for complex seal arrangements, especially where the sheet enters and leaves the dryers, and the trouble which may occur clearing jams if there is a break in the drying section.

5B.6 MACHINE SPEED AND DRAW CONTROL

If the speed of a machine is increased while making a particular grade of paper, for moisture at the reel-up to remain the same the rate of evaporation in the drying section must increase *pro rata*. This is achieved in practice by some increase in the steam pressure in the cylinders, but it has long been realized that the actual increase needed is much less than would be required were the higher pressure solely responsible for producing the greater evaporation rate. The reasons for this will now be discussed.

5B.6 1 Changes in drying conditions with increased machine speed

To understand what happens in the drying section when machine speed is increased, it is necessary first to consider drying on an individual cylinder. Reference to Fig. 5.5 shows that a certain proportion of the surface of a cylinder is utilized for raising the temperature of the web, and it is only in the later portion of the dryer surface that temperature levels off and a reasonable evaporation rate can be achieved. With an increase in speed a greater rotation of the cylinder occurs in a given time, so with other conditions constant the same heat can be transferred through the cylinder only after the paper has travelled further round the dryer. In other words, the proportion of the cylinder needed for heating up the web increases, leaving

less area available for evaporation at near-maximum rate. Consequently a rise takes place in the moisture content of the web leaving the dryer. Figure 5.28 shows experimental results reported by Jansen and Nordgren (35) which illustrate this.

Although with an increase in speed the reduction in moisture content of the web achieved by an individual dryer is thus diminished, the capacity of the dryer, i.e. the total water evaporated in unit time, actually increases. In other words, doubling speed with all other conditions the same does not lead to a reduction by half in the difference between the moisture content of
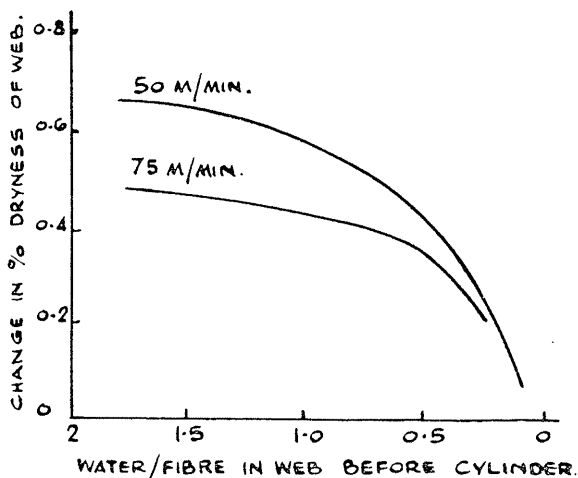
Fig. 5.28. The increase in dryness of a web passing over a drying cylinder at two different speeds for varying moisture content before the cylinder (after Jansen and Nordgren)

the web entering and leaving the cylinder. This is primarily due to the increased heat transfer that must occur (for the same internal temperature) when the average temperature on the cylinder surface decreases as a result of the longer heating-up period; thus, at any point round the cylinder circumference the outer temperature will be lower at the faster speed, hence the heat conducted through the cylinder in unit time will be greater. In addition to this effect, felt covering a given area is required to receive a lower quantity of evaporated water, and thus may provide less resistance (if any, that is) to transfer of further water into the layers adjacent to the sheet.

To compensate for the lower quantity of water removed from a given area of the web, the steam pressure of the cylinder has to be increased. It does not follow from this that the efficiency of the drying section is drastically altered; in fact, except insofar as a greater steam pressure implies higher operating temperature and therefore leads to slightly greater heat losses, the weight of steam needed to evaporate unit weight of water in the web should theoretically be unaffected by the speed of the

machine. The usual difficulty that occurs is caused simply by the steam pressure rising to a point where it reaches the limit of what can be supplied.

In practice though, as the machine speed increases a change takes place in the amount of evaporation occurring in the different parts of the drying cycle for each cylinder, and a greater proportion of the total evaporation occurs in the open draw between cylinders as opposed to on the cylinder itself (partly this is a consequence of quicker evaporation due to increased
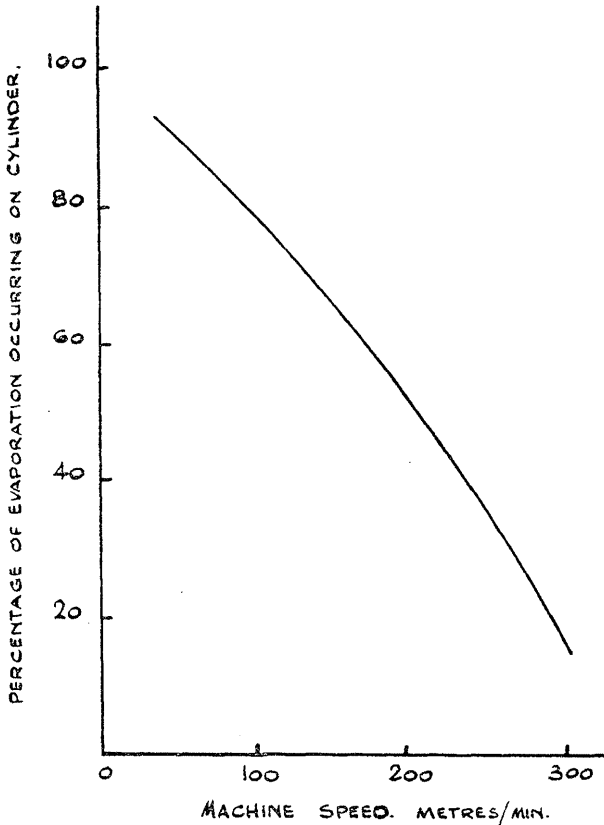
Fig. 5.29. Relationship between the percentage of total evaporation occurring on drying cylinders with the machine speed (after Jansen and Nordgren)

air velocity relative in the sheet). This change in character of the drying may be expected to have a more direct effect on the efficiency of steam utilization. Figure 5.29 (though based on only a small amount of data from different sources) gives an idea how much the amount of evaporation occurring while the web is in contact with drying cylinders, as opposed to the open draw, alters with increasing machine speed. Due to this effect, the

increase in cylinder steam pressure necessary to sustain higher machine speeds is kept within manageable limits, and it is evident that ventilation conditions in the cylinder pockets become more and more important as speed increases.

It has been suggested that the draw between the cylinders of higher speed machines should be lengthened to assist evaporation in this region. But most water evaporating from the web does so by flashing off almost immediately after leaving the cylinder (this is demonstrated by the rapid fall in web temperature shown in Fig. 5.5); also longer draws become more difficult to manage. It is therefore unlikely that much improvement would follow from deliberately extending draws beyond the length demanded by the geometry of the cylinder spacing.

To improve the evaporation taking place actually on the cylinder surface, some increase in drying cylinder diameter appears desirable for machines running at high speed. This is usually needed anyway as the cylinder must withstand greater steam pressures and remain in balance dynamically at a higher speed of rotation. Theoretically, if no other effect were present the diameter would need to increase proportionally with the speed in order to maintain the same rate of drying round its circumference, But at high speeds this would soon require cylinders of inconvenient size. and also the effect of felts may well diminish because (for the same tension) pressure on the cylinder reduces as the diameter is increased.

5B.6 2 The influence of draw

In the drying section, the draws between different sections and between the last bank of dryers, the calenders, and the reel-up are generally very small compared to customary draws in the press section. In most cases they do not exceed at most 1 per cent. at any single draw. But it is equally as important to have a satisfactory control on these draws because relatively quite small changes can bring about a significant alteration from the point of view of shrinkage of the web. As the paper dries, its extensibility under a given tension reduces; this means that a particular degree of change in the draw has a much greater effect on the tension of the web in dryers compared to the presses—in other words, the draw is more sensitive in the dryers.

Changing the draw between different parts of the drying section and calenders affects the amount of web shrinkage in the machine and cross direction which is permitted to take place. This not only has a direct effect on the reduction in deckle of the paper and hence on production, but also changes occur in the strength properties of the paper to a degree dependent on the magnitude of natural shrinkage that would occur were the paper able to dry free from tension. It also affects anisotropy of the paper. These and related topics have been fully discussed in the theoretical section.

As it is important in this part of the machine that draw is adjusted to keep the tension in the web as steady as possible, a strong case can be made out for having an indication of the tension at each draw; in fact, it is probably more important to have this than a draw measurement, though

the latter is also valuable as an indication of changes occurring in behaviour of the sheet. The simplest method of indicating tension is from a full-width or narrower free-riding roll, the journals of which act against restraining springs; the position of the roll then gives an indication of the tension in the web and the movement may be magnified to give a suitable means of display in any convenient manner. Alternatively, strain gauges (load cells) in the roll supports may be used to give a direct measure of the force exerted on the roll by the web, and in this case movement of the roll itself need only be very small.

Changes in stock composition, particularly those associated with free-ness, affect the natural shrinkage occurring during drying quite closely, and in a poorly controlled stock preparation system the tension of the web between draws may fluctuate continually; this necessitates repeated alterations to the draw to maintain a steady tension. On machines making grades of paper in which shrinkage properties have to be closely controlled and repeatable, it would be useful to control the tension by automatic changes to the draw. The feasibility of this depends entirely on the method of obtaining the draw and also on the type of drive.

5B.7 PAPER PROPERTIES

The performance of the drying section is directly affected by certain characteristics of the paper. This is because, particularly in the later stages of drying, the fibre network structure comprising the web influences the rate of migration of water through the sheet and hence the ease of drying. In this respect, the quantity of steam required to evaporate a unit weight of water and the general shape of the drying curve, i.e. the value of moisture content as the sheet progresses down the dryers, differ considerably for different grades of paper; several examples for various types of paper have been reported by Montgomery (11) and it is interesting to note that the shape of the drying curve for each grade is generally similar for different machines, thus confirming the relative importance of the paper structure.

Apart from this, the main effect on drying of changing paper properties, certainly during any one making, is indirect and depends essentially on changes in the moisture content of the web entering the dryers. If this moisture content increases, then the quantity of water requiring evaporation in the cylinder section also increases and a greater volume of steam is necessary (though not a *pro rata* increase—see 4I.1). Moisture content leaving the presses is dependent to some extent on moisture content at the couch, and this in turn is affected by drainage conditions on the wire. Further, the performance of the presses themselves depend on the characteristics of the paper; for example, other things being equal an increased freeness in the stock gives an increase in dryness of the sheet leaving the press section.

Due to these effects, changes in the structural properties and composition of the paper running on a particular machine have a definite influence on steam demand. For this reason it can be particularly valuable to have a measure of the flow of steam to the drying section for comparison with

various other measurements indicating, for example, drainage conditions on the wire and performance of the presses; over relatively long periods changes in steam pressure and flow are likely to be a direct consequence of differences in demand caused by an alteration of the moisture content of the web entering the drying section (particularly this is so when moisture content at the machine reel-up is well controlled), and the reasons for these changes can more readily be traced when a record of steam usage is available.

5B.8 THE M.G. CYLINDER

The M.G. cylinder (Yankee cylinder in the U.S.A.) was first developed to impart a one-sided, highly smooth finish as an integral part of the making machine, hence the term 'machine-glazed'. This is still the primary purpose of the cylinder when used for such grades as kraft and sulphite wrappings, envelope and bag papers, etc., though the M.G. is also used extensively on tissue machines. This is primarily because of the high rate of drying that can be achieved, but also because it enables open draws to be avoided, at least until the web is almost dry and sufficiently strong to withstand the tension developed at the high speeds of manufacture associated with this product. On some machines a more specialized function of the M.G. cylinder is to introduce a crêpe effect.

In this section it is proposed to discuss aspects particular to the M.G. cylinder, as opposed to the ordinary drying cylinder. Arrangements for steam supply, hoods, and condensate removal, in so far as they differ from multi-cylinder drying, have already been mentioned in the appropriate sections.

5B.8 1 General comments on M.G. cylinders

The M.G. cylinder can be the only form of drying on a machine, but it is increasingly common nowadays for a number of conventional drying cylinders to be incorporated before or after the M.G., occasionally both. This enables an increased production to be attained, and also permits more flexibility in determining the degree of gloss imparted to the paper. After-dryers are particularly common on machines making crêped paper because it is easier to produce the crêpe effect when the paper is slightly damp; in such cases a negative draw is needed between the M.G. and the after-dryers (continuous indication of this draw in some form is an essential prerequisite to successful production of this grade). Some machines are constructed so that the position of the reel-up can be quickly adapted to leave out after-dryers when required; this facility permits a useful extension of the range of papers that can be made on the machine.

The size of the M.G. dryer makes it easy to lead the web on to the cylinder quite close to the bottom, thereby utilizing as much of the surface as possible. However, this does mean that the wire side of the web contacts the M.G. surface, and with Fourdrinier papers this is always initially the rougher of the two sides so inevitably the contrast obtained is not quite so great. To attain the maximum two-sided effect, the top side has to contact

476

the M.G.; this either involves rather clumsy felt runs and draws at both sides of the cylinder, or the M.G. has to be sited low down in a basement, both rather unsatisfactory arrangements. Earlier M.G. cylinders were covered with a felt but this practice, never very easy to operate nor particularly efficient, is probably now obsolete and has been replaced by hoods of the ordinary and H.V. type.

Care of the cylinder surface is one of the most vital features of M.G. operation because any blemishes on the surface are readily transmitted to the paper. Doctors, wire scrubbers, emery cloth, and other materials are used continuously to keep the surface burnished as the cylinder rotates, while other devices such as the electro-doctor which prevents corrosion by applying an electric charge to the cylinder surface are claimed to be of value in certain operating conditions. A more drastic operation involving buffing first with coarse then with finer-grit wheels, followed by other methods of polishing with lubricants, is used periodically to brighten up a surface dulled by constant use. The treatment most suited to any particular M.G. cylinder must be found by experiment as deterioration of the surface depends very much on the grade and contacting moisture content of the papers and on characteristics, particularly hardness, of the water used at the mill. The ideal degree of burnishing keeps the cylinder adequately smooth and bright without too drastic an action; excessive polishing of the surface is not necessary and beyond a certain point does not enhance the gloss imparted to the paper.

The size of an M.G. cylinder makes it necessary to be manufactured with a thicker wall than ordinary dryers to an extent dependent on the dryer diameter and the strength of the metal. This produces an increase in the resistance to transfer of heat through the cylinder wall, and to overcome this and obtain a satisfactory temperature at the outer surface, higher steam pressures are necessary. But higher internal pressures in turn produce greater stresses which the cylinder must withstand, and mean that the wall thickness has to be increased still further. The best compromise in thickness and operational steam pressure to overcome this vicious circle has been the subject of much calculation and discussion which is too specialized to consider here; an article by Chapman (51) may be referred to for a summary though no straightforward solution appears to be available yet. The size and thickness of the M.G. cylinder also make it essential to prevent rapid changes in temperature in order to avoid setting up thermal stresses; for this reason M.G. dryers are usually kept warm over a shut week-end and heating up in preparation for start-up has to be at a very carefully controlled rate (nowadays frequently using an automatic device which controls the rise in temperature to a pre-set pattern).

To overcome the natural deflection of the cylinder on its journals, a camber is put on the surface which as closely as possible corrects for this at normal operating temperature. Uneven action of doctors can produce changes to this camber which ultimately lead to running problems; the camber must therefore be checked at intervals and corrected when necessary by grinding. Larger M.G. cylinders are slowly rotated when the machine is shut to prevent distortion under their own weight.

There are normally two or three doctors on the cylinder serving different purposes. Apart from helping to keep the cylinder clean and polished, doctors have a variety of functions: to hold emery cloth against the surface, to hold a damp felt for easier removal of fluff and dust (a steam jet immediately in front of an ordinary doctor sometimes serves the same purpose), for crêping (with a special doctor adapted for rapid changing because the high angle of contact produces rapid wear), and for cutting off the paper above the crêping doctor when the latter is being changed. These doctors require much closer attention than do doctors on ordinary dryers and merit a careful record giving details of their life and the frequency of changing so that the effect of alteration in hardness, angle of contact, load, etc. can be examined. Oscillation is absolutely essential to prevent the possibility of scoring the cylinder surface. The load on the doctors should also be easily adjustable and examined frequently.

5B.8 2 The pressure roll

Intimate contact between the web and the M.G. surface is obtained by pressing the web hard on to the cylinder with a 'pressure' roll. This is an essential and critical part in the operation of any M.G. cylinder, and it is the close contact achieved in this way which is responsible for the high evaporation rates associated with M.G. dryers—generally about double the equivalent rate over the same area of ordinary felted drying cylinder. The closeness of contact also governs the glazing effect of the cylinder.

Pressure rolls are made of rubber and are cambered to suit the pressure normally applied. Systematic attention to the camber is extremely important for obtaining an even gloss across the web and keeping the felt properly guided; records for pressure rolls must be kept with as much care as for press rolls. Occasionally a suction pressure roll is used, mainly to help in preventing the web from being thrown off as it rotates round the roll, but this practice appears to be confined to machines making crêpe paper because shadow-marking may be noticeable in a flat sheet. Some M.G. cylinders operate with two pressure rolls, the first to transfer the web to the cylinder and the second (using the same or a different felt) to improve intimacy of contact, but the value of this is not certain and trouble can occur with air-blowing and distortion of the sheet at the second pressure roll.

The pressure applied at a pressure roll closely affects the resulting gloss of the paper. Chapman (51) devised a simple laboratory experiment giving a static simulation of M.G. operation and obtained the results shown in Fig. 5.30; gloss was measured on an Ingersoll glarimeter. He also reports that a programme of increasing M.G. nip pressures on a number of machines lead to a substantial increase in average gloss. The curves in Fig. 5.30 indicate that improvement in gloss with increase in pressure approaches an asymptotic value so there is obviously a limit to the degree of improvement possible in any particular case.

For a given load on the roll the pressure varies with nip width, and hence with the felt condition and hardness of the rubber used in the roll. Normally a relatively hard nip is desirable to attain maximum gloss,

though on some grades where this not important, e.g. crêpe, a softer pressure roll and more compressible felt help to secure more uniform adhesion across the machine at the crêping doctor and can therefore be preferable. The load applied to the front and back sides of the roll can easily be measured, directly or otherwise as with press rolls, and it is general practice to have an indication of this.

The type of felt used in a pressure roll nip is partly controlled by the press conditions (the same felt passing through the final press and the M.G. nip); on some grades the felt is also used to vary the top side finish of the paper,
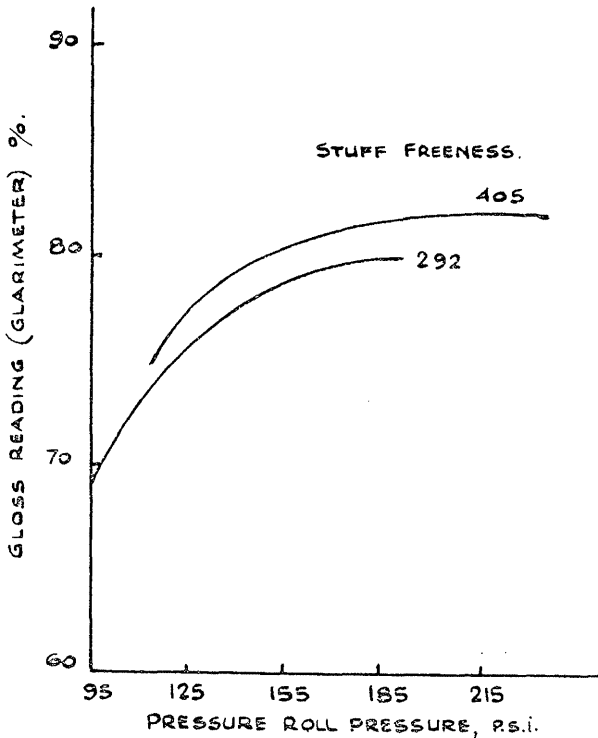
Fig. 5.30. Gloss variation of an M.G. paper at various pressure roll pressures and stuff freenesses (after Chapman)

the appropriate face of the felt being woven in a special pattern, e.g. ribbed or rough. Ample cleaning equipment is needed for this felt to avoid adhesion difficulties as gradual plugging occurs throughout its life (the sheet then tending to follow the felt on the trailing side of the pressure roll nip); also the variation in gloss that results from narrowing of the nip width as the felt becomes less compressible with age is minimized by keeping the felt uniformly clean. Continuously operating full-width

showers with the addition of a small quantity of detergent (as for ordinary press felts) are likely to be the best means of achieving this, especially on machines where the web is couched and carried on the same felt through the press section and on to the M.G. cylinder.

5B.8 3 Factors affecting the gloss imparted by an M.G. cylinder

The gloss imparted by an M.G. cylinder is frequently the most important reason for its use. Two factors affecting the gloss have already been mentioned: the smoothness of the cylinder surface and the pressure applied at the pressure roll. Other variables will now be discussed.

The moisture content of the web when first contacting the M.G. cylinder is very important. Chapman cites an example of the effect on a plain kraft paper of decreasing initial moisture content over the range 50 per cent. to 47 per cent.; the gloss diminished appreciably as the moisture content was reduced, particularly towards the drier end of the range, and the general appearance of the sheet also deteriorated and exhibited more cockling. Other reports indicate that low initial moisture content in the web also leads to poorer contact (with consequent lower drying rate, though as less drying is needed anyway this may not be a disadvantage); in addition, a more uneven glazing effect is observed (presumably due to less uniform contact and greater sensitivity to moisture content variations across the machine). To avoid these disadvantages the presses may in some cases have to be raised or not used at all in order to increase moisture content at the M.G.; more commonly, on faster machines the temperature of a number of pre-dryers is varied to suit conditions, though too many pre-dryers can become a nuisance because occasionally it may be found difficult to reduce their drying effect sufficiently.

The moisture content of the sheet when leaving the M.G. cylinder also affects the gloss, this being greater when the paper is taken drier off the cylinder. Thus the overall drop in moisture content over the M.G. has an important effect on the gloss attained: if the moisture drop is reduced, either by lowering initial moisture content or raising the leaving moisture, then the level of gloss will to some extent fall. The drying rate of an M.G. cylinder is therefore a critical factor in determining the production possible for a given quality: a deficiency in the drying rate of the M.G. though it can be made up by using more steam in either or both pre- and after-dryers, is overcome only at the expense of a loss of gloss which may be unacceptable. All that can be done in such circumstances is to pull back the speed to permit the M.G. cylinder itself to reduce the moisture content of the web by an amount sufficient to give the gloss required.

After-dryers are generally used only for papers requiring a low glaze. But apart from this, if the moisture content at which the sheet is pulled off the M.G. is too high, problems with adhesion to the cylinder occur. Adhesion has been found to depend closely on moisture content, reaching a maximum at around 30 per cent. moisture depending on the grade of paper and condition of the metal surface; thus if the machine is run in such a way as to cause the sheet to be too damp when it is removed from the M.G., the

high tension necessary to overcome sticking can cause rupture problems and the paper surface may be disturbed.

Other factors affect the gloss to greater or lesser extent. According to Chapman, if the fresh stuff becomes freer or if the proportion of moist pulp is increased, in both cases average gloss is raised. Occasionally spraying the pressure roll felt with steam or water is found essential to obtaining a satisfactory gloss, but this presumably is simply a result of increasing moisture content of the web at the pressure roll nip.

Oil or glue is sometimes sprayed on to the M.G. surface to improve adhesion and this also gives an improvement in gloss, possibly by virtue of the improved rate of drying which allows the initial moisture content of the web to be raised. This practice is also used for crêped papers, it being claimed that the better adhesion gives an improved crêpe effect.

5B.9 CALENDERS

In this section some general points concerning calender operation will be discussed. Calenders are used primarily to improve the overall smoothness of a sheet of paper and in any particular stack two principal factors affect performance in this respect: the number of nips and the moisture content of the paper. Both these have been dealt with earlier in the theoretical section. A secondary function of calenders is to assist, by use of the air blowers, the building up of an even machine roll, i.e. a roll which bulks uniformly over its full width; this aspect will be touched on below, though a full consideration of the use of calender air blowers is left till 5C.4.

On some machines calenders are used for applying colours, starch solutions, wax emulsions, and so forth to the web surface from water doctors. The purpose of this is to improve surface smoothness and appearance, and other characteristics such as oil penetration or scuff resistance; these are essentially finishing processes which it is found more convenient to undertake on the machine rather than as a separate operation—as such they fall beyond the scope of this work.

5B.9 1 General comments on calenders

The size and number of stacks on a paper machine is governed entirely by the maximum degree of smoothing that is required. Some older machines are equipped with as many as five sets though it is unusual nowadays for there to be more than two on new machines. There are several reasons for this, most important of which are the difficulty of running several stacks together at faster speeds, the development of supercalendering as a more flexible means of obtaining a high final finish, and the growing size of machine calenders which enables a higher finish to be achieved in any individual stack.

Another reason likely for the reduction in the number of calender stacks is that nowadays as a result of improved overall machine control paper tends to be run with more moisture at the reel-up, and this increases the smoothing effect of calenders. On machines equipped with several sets of calenders paper may be run through each stack at an average moisture

481

content of 3 per cent. or lower, and the increase in smoothness occurring at any one stack will then be quite small. On the other hand, when calendering at such a low moisture content, the loss of bulk for a given increase in smoothness will not be so great; thus, any required final smoothness can be achieved for less loss of bulk than would occur were the moisture content higher and fewer stacks used, a distinct advantage in almost all categories of paper.

Any load applied to a calender stack adds to the weight of the rolls themselves, increasing the pressure at each nip and hence improving the resulting smoothness. This gives some measure of control on the final finish though it is not good practice to change the calender loading except within relatively narrow limits otherwise difficulties inevitably occur due to unevenness across the web (the problem of cross-web control of thickness and smoothness is discussed in 5C.4). Instead the general level of finish required for any one making is achieved by missing out nips or whole stacks of calenders, and final trimming only is done by altering the load on the calenders. Where a variety of grades are made on a machine, several sets of calenders can thus give much greater flexibility. For the maximum finish the load on successive stacks of calenders must be increased in steps to offset the reduced effect of a given load when the paper is smoother entering the stack (from this it follows that later stacks should be heavier); Mardon (106) has even reported that a second stack with a similar loading to the first has practically no effect, and considers that further development is achieved only when nip pressure in the second stack exceeds that in the bottom nip of the first stack. The first set of calenders normally has the greater influence on the reduction of thickness or bulk, just as the first nip in any particular stack has the greater influence on this property. Later stacks affect surface properties more and should, according to Mardon, be equipped with smaller rolls that can be adequately loaded; this gives the higher specific nip pressure which appears to produce more rapid increase in smoothness.

With increasing machine speeds and deckles, calender rolls have become gradually larger and heavier. The open-sided stack is now replacing the A-frame design typical of older machines and has distinct advantages in making it easier to change rolls and ensure correct alignment one above the other. Bearing lubrication has advanced from ring oiling to gravity and forced-feed oil. Bottom roll bearings and occasionally others are generally water-cooled.

Some calenders are equipped with two or more hollow rolls through which steam is passed; normally these are arranged to contact each side of the sheet in equal number. A sight-glass and steam trap are usually provided and the system is commonly a simple blow-through arrangement with the rolls in parallel or series and pressure gauges at either side. Condensate is returned to the main system, though when a higher pressure than the main steam supply is used (to raise the useful temperature inside the rolls) the exhausted steam may be passed into the main dryer header; however, this practice can lead to difficulties when back pressure varies, and it is preferable to use the low-pressure exhaust steam for some other purpose

such as heating broke pulpers or breakers at the dry end to assist dis-integration of the broke. It is also possible, though unusual, to heat calender rolls by gas or electricity.

However, the usefulness of steam-heated rolls is open to a certain degree of doubt. Certainly the use of steam at start-up can help to heat up the rolls to nearer normal operating temperature and thereby cut down on the time needed to run the stack beforehand when there is no paper in the nips (a practice which is harmful to the surface of the rolls). But it is also fairly common procedure to keep some steam flowing through the rolls all the time, on the supposition that this gives an improved smoothness and gloss. By contrast, on other calenders cold water is run through one or more rolls, and this is reputed also to give a smoother sheet, though without added gloss. So far as the author is aware, experimental evidence has been pub-lished to confirm the validity of only the first of these practices, see 5A.43.

5B.9 2 Calender roll cooling

It is common practice to use low-pressure air for cooling one or more rolls in a calender stack at selected positions across the machine. Where a jet of air is directed on to a roll, the natural heat generated in the roll by frictional resistance and deformation is dissipated more quickly, resulting in a lowering of temperature in that region. The effective diameter of a roll at any particular position is dependent on the temperature through the cross-section and any reduction in this temperature, even if only near the surface, will cause the diameter to be fractionally, but proportionally, reduced also. Calculation of the precise effect which occurs in practice is difficult because it is only possible to measure the surface temperature of calender rolls where air will have the greatest effect; but as an example, a 10 deg. F temperature reduction in a 14 inch roll would, if distributed through the full area of the roll, reduce the diameter by the order of one thou., which is appreciable compared to paper thickness. The effect of this diameter reduction is to increase the gap between rolls adjacent to the one being cooled, so wherever air is directed on to a roll a slight decrease in calender-ing pressure occurs, causing less reduction in thickness of the paper passing through in this position.

The cooling effect of a jet of air depends on the velocity and the tempera-ture difference between air and roll (according to Howe and Lambert (61) the temperature difference is not so important relatively). By varying the velocity of the cooling air at different positions across a machine it is thus possible to alter the thickness profile of the paper. In practice, of course, the most desirable situation at the reel-up is where thickness is as even as possible, since this makes it easy to build a machine roll of uniform tight-ness all the way across; so the rôle of the calender cooling equipment is essentially to correct unevenness in the thickness profile. Such unevenness can originate either in the paper itself or because the calender rolls are a different diameter in one place than another: in the former case correction of thickness may lead to deterioration in the cross-web profile of smooth-ness and other qualities; only when air is used to remedy uneven thickness resulting from differential diameter of the rolls (poor cambers, lack of

uniformity of heating-up due to cooling effects, etc.) is there likely to be an all-round improvement in cross-web paper uniformity. This will be discussed in greater detail in 5C.4.

On slower machines making heavier grades, several large air blowers at intervals of one foot or less may be sufficiently flexible to give adequate control; with this arrangement a relatively crude valve on each individual blower enables the flow of air from the main header pipe to be regulated, and in addition the nozzle can usually be tilted sideways so that three or four may be concentrated on one spot if need be. For high-speed machines it is advantageous to use a greater number of nozzles which are smaller in area and closely spaced at intervals of 2 inch to 3 inch making tilting unnecessary; in modern designs the nozzles are incorporated for convenience with an oscillating doctor using the frame as an air duct. To assist the dryerman in keeping a more systematic watch on the amount of air he is using at different positions across the machine, the air pressure in each nozzle can be measured on simple gauges or water manometers which are displayed where they can be easily seen as the roll is checked for uniform hardness of reeling.

Normally there are two sets of cooling nozzles on the entering side of the calenders, one of which will be on the third roll up and the other usually on the fifth roll. In some designs the nozzles are on the leaving side of the stack and then one set may be directed on to the second or queen roll. Choice of the actual rolls on which air nozzles are used does not seem to affect the result materially provided the air blows direct on to the roll itself (paper of course has an insulating effect). Blanchard (82) considers that air should be blown on to higher rolls in a stack since it is in the early nips that the greatest caliper change occurs. But it may be that thickness differences introduced so soon in the stack are nullified in later nips. Possibly the best arrangement from a theoretical standpoint is to have one set of nozzles on the roll next to the top where differences in thickness of the paper itself are remedied, and one set in the middle of the stack to remedy diameter differences of the calender rolls. But how the two functions could in practice be separated is another matter!

Pressure of air used for calender cooling is usually about 1–2 p.s.i. on the modern narrow nozzles, though on larger blowers pressure is not usually greater than $\frac{1}{2}$ p.s.i. The air should be well filtered to avoid abrasion and marking from grit particles entering the calender nips. In some cases the air is cooled, though this is hardly necessary in this country; it may even be a disadvantage to cool the air for there are indications (104) that maximum smoothing effect is achieved in the 70 deg. to 75 deg. C region and this is hotter than the normal operating temperature for calenders. Temperature control of the air has been advocated but this degree of elaboration cannot be justified unless it is apparent that normal changes in ambient air temperature have a significant effect. This seems unlikely because such changes would have to be quite large to alter the difference in cooling effect as between the various nozzles across the machine; in other words, alteration of cooling air temperature can be expected to have only a second-order effect. Some heating may be found desirable when the

cooling air is very cold to avoid the nozzle valves becoming too sensitive, but this can be easily achieved by drawing a proportion of the intake-air from the machine room.

5B.9 3 Barring caused by calender stacks

With increasing machine speeds the difficulties associated with barring at calender stacks have become more and more pronounced and many groups have carried out research to throw light on the causes of this. Barring appears on calender rolls as alternate light and dark patches stretching the full width of the roll at intervals of about one inch or more; it generally starts either down the whole stack at once, or on one or two intermediate rolls from which it appears eventually to spread over the whole stack. Connected with the presence of these bars is the occurrence of cyclic variations in thickness and surface properties of the paper in the machine direction; these variations are more pronounced the greater the moisture content of the web (due presumably to the greater effect of calenders), and in several cases blackening occurs in the areas of low thickness and bars are observed very prominently in the paper itself.

The difficulty in tying down the cause of barring is that the severity and frequency of the cyclic variations produced in the paper can vary over quite a short space of time: they are sometimes quite regular but at other times are apparently irregular in appearance with periods of large fluctuations in thickness interposed by periods of relatively little variation. Also the amplitude of bars on the rolls themselves may, according to Pye (96), differ from one calender roll to the next and can fluctuate in prominence or even in amplitude over a period of time; further, the amplitude of bar marks in the paper can be quite different again from those on the rolls. Despite this elusive behaviour, it is now firmly established that there is an association between bars that appear on calender rolls, and barring in the paper (in the sense of cyclic thickness variations, not substance barring such as is produced at the wet end): both in fact originate in small vertical oscillations or 'chatter' of the rolls in the calender stack and the questions to be answered are how do these vibrations originate and how best can they be overcome?

Analysis of thickness profiles in the machine direction to assess barring in the paper web is confused by cyclic fluctuations in substance produced at the wet-end because these may also be associated with thickness variations. This has led some workers, notably Howe and Cosgrove (87) and Pye, to suggest that cyclic variations in substance can be responsible for creating barring; this would occur when a resonant vibration in the stack is excited due to the amplitude of successive low substance regions being some simple fraction of the calender roll circumference. On the other hand, Cuffey (83) failed to find any connection between calender stack vibration and cyclic substance variations in the uncalendered sheet. There is more general agreement that stack vibration can be set up by all kinds of external oscillations similar to those produced by reciprocating and rotating machinery at the wet-end of the machine.

Wahlström (98) considers that vertical vibration in calenders is essentially a characteristic of the stack itself; it is not necessary to postulate any continuous outside disturbances such as periodic variations in the uncalendered paper or mechanical vibrations transmitted from other machinery to explain the oscillations which are observed. The calender rolls float, as it were, supported by the paper which acts in each nip as a spring possessing some normal pressure-compression relationship; analysis of the dynamic behaviour of such a system using measured compression characteristics of paper and the weight of rolls in a particular stack showed that stable oscillations could be produced which agreed well with those observed in practice. Once excitation has been started in a nip (substance variations or external vibration may have a rôle in this), the oscillation can be transmitted through the whole stack which begins to act as a mechanical oscillator using the paper itself to transmit the forces and act as a feed-back medium. The frequency of stable vibration of such a system will vary according to many local conditions, including the machine speed.

Persistent oscillations at specific frequencies will eventually mark rolls, and may become self-perpetuating because of this. According to Howe and Cosgrove, the marks themselves are due to differential work-hardening, though Pye is of the opinion that they are produced largely by the effect of the vibrations on doctors acting on the rolls. The optical appearance of bars on the rolls depends on the angle at which they are viewed, and in fact they comprise smooth and rough strips, the latter exhibiting fine, short scratches and minute pitting. Parker (117) has detected definite corrugations with severe pitting centred usually in the troughs on the upgoing side.

So much for the sources and nature of barring, but how can it be prevented or reduced to tolerable limits on machines which are plagued with this trouble? Numerous remedies have been suggested. Staggering rolls alternately a fraction of an inch off-centre up the stack appears to help delay the onset of barring difficulties (and also, incidentally, gives a better fit if bearings are slack). A modern development of this technique (using a 'Torque Compensator') is in fact claimed to present a most efficient prevention of barring (118). Also, according to Cuffey, changing the number of rolls may disturb the resonant frequencies sufficiently to be helpful, though he reports that adding or removing a roll can have the opposite effect on different stacks. Alteration of the relieving or applied load on the stack may also help temporarily to disturb a persistent, severe chatter (as may making the stack jump by passing through a thick wad of paper), but normally changing nip pressure in this way succeeds only in shifting the frequency of vibration. Removal of grit from the paper stock reduces barring by preventing rapid wear of calender rolls, and grinding should be carried out on perfectly circular journals or initial corrugations can be imposed (117).

The most direct remedy for calender barring is to prevent or damp the vertical vibration movement of the rolls which is recognized as the basic cause. To this end, Wahlström has constructed a device for replacing the top roll by a light hollow roll (one-tenth the weight of a normal calender roll) which is pressed upon by a number of other small rolls forced down by

air cushions. The nip pressure at the top then becomes relatively independent of vertical movements in the stack, and the feed-back mechanism essential for setting up a regular oscillation down the whole stack is largely eliminated. Use of this device is reported to have been very successful in reducing barring though further applications have not yet been reported.

5B.10 EQUIPMENT

To complete discussion of operating factors which affect performance of the final section of the Fourdrinier, it is now proposed to bring together a few miscellaneous points regarding equipment found on all machines. In addition to this, the use of devices of a more specialized nature including such equipment as the smoothing press, breaker stack, sweat roll, and so forth is briefly described.

5B.10 1 Drying cylinders and drive

Various details relating to the drying cylinders have already been given in various contexts, in particular with regard to their size and number on any machine and the factors governing their construction. Normally all cylinders on a machine are of the same size, with the possible exception of the last few where on machines running a small range of similar grades the diameter may be gradually reduced a total of 0·1 in. or more over the last 8 or 10 cylinders in order to offset the effect of shrinkage. Also the first or pony cylinder can be of smaller diameter, being then more suitable to give a first gentle application of heat to the web; this arrangement is generally considered superior to having an unheated small-diameter turning roll and a normal-sized first cylinder because wrinkling of the web and surface picking is less likely to occur. Cylinder material is cast-iron, except for machines operating at very high steam pressures (above about 80 p.s.i.) when fabricated steel may be employed. This material is also used in the Lukenwald dryer which consists of a jacket formed by an outer and inner shell; steam is introduced into the jacket through a number of ribs connecting with the journal and condensate is removed through a fixed pipe attached to the inner shell. This construction allows the use of relatively thin steel even for high steam pressures, thereby giving a faster evaporation rate than with an equivalent cast iron dryer, and the greater velocity of steam in the jacket is claimed to produce a more uniform temperature across the face of the roll. It is important that all cylinders are accurately balanced for smooth rotation and aligned parallel with one another.

Sectionalization of the cylinders has also been discussed earlier; its use is generally to permit some control on shrinkage and reduce the possibility of the web creasing and breaking. On smaller machines splitting the dryers presents no special problems except for the cost of providing separate drives for each section; a greater variety of felt lengths may be necessary but the total cost of storing and using should not be appreciably greater than if fewer sections were used. Nevertheless there is no advantage to be gained from having an unnecessary number of sections because control of the draw at each is equally as important as when fewer sections are used:

thus, more draws in the drying section necessitate either a more expensive instrumentation and control system or place greater demands on the dryerman. On faster machines the governing factor in deciding the number of sections is often the maximum number of cylinders that can be controlled in any one section. Too many cylinders ganged together makes the drive unwieldy and places a strain on the gears. This may be overcome by removing gears and restricting the drive to only a proportion of cylinders in each section, relying on the felt to pull round the remaining cylinders. To prevent any possibility of slippage the felt tension will then probably have to be higher than otherwise, and some difficulty, especially with ropes, may be experienced when stopping the section quickly due to the tendency for the undriven cylinders to lose speed more slowly. On the other hand, creasing of the web between cylinders due to small unevennesses in transmission through individual gears can often be substantially reduced by this modification.

The drive is an especially critical aspect of the drying section, smooth operation being closely dependent on the sensitive and uniform control of draws produced by very small speed differences between the sections. Ideally it should be possible to alter the draw at any section without affecting any others, though on most older machines this is not possible and adjustment of one draw generally means that others will need re-setting also; it is frequently the case that one of the presses is taken for the master speed-setting and in this event alteration of, say, the draw between the last press and first section of cylinders means that each succeeding draw down the dryers to the reel-up will also require attention. Facilities for crawling the dryers are essential for putting on new felts and for the purposes of inspecting the felts and helping to heat up cylinders evenly at start-up. It is also very useful to be able to reverse the drive as this facilitates removal of broke jammed in the cylinders. Modern electric drives can have other valuable features such as a controlled acceleration up to the speed desired, controlled braking, and means of temporarily overriding a pre-set draw during feeding up in order to remove the slack quickly and thereby lessen the risk of breaking through excessive flapping. One or more emergency stop-buttons in prominent positions by the dryers are an important safety measure, and on faster machines help to prevent jams becoming too serious.

5B.10 2 Doctors in the dryers and calenders

Doctors are important on the first few dryers to keep down build up of scale, pitch, fibre, dust, etc., on the cylinder surface and prevent the sheet wrapping round and jamming or bulging the felt in the event of a break; frequently it is necessary to equip every dryer with a doctor for these reasons. Suitable trays, particularly for top dryers, are also needed on the first few doctors in order to collect the debris scraped off the cylinder and so prevent it from contaminating the sheet and causing breaks especially in the calenders; such trays need attention and must be regularly cleaned. More modern applications include a suction arrangement incorporated in

the doctor to remove the debris as soon as it is formed by use of a low-pressure air flow through a tube behind the doctor which carries dirt away to an extractor fan; this type of doctor, though more expensive than the simpler type, has much to commend it for the first few dryers. Another innovation is the electro-doctor which prevents corrosion of the cylinder surface by inducing an electric charge on to the surface; this is, however, more likely to be of value on M.G. cylinders where retention of a polished surface is much more critical.

A doctor on the final cylinder of the drying section or any section preceding a gap in the dryers for a breaker stack, size press, etc., is usually essential to ensure that the sheet does not wrap round at a break or start-up; it is often of a heavier design than on other dryer doctors. Where the final cylinder is used as a sweat roll and a film of moisture on the surface is necessary for its operation, it is not possible to have a doctor applied continually; in this case some mechanism to detect a break and immediately apply the doctor is needed.

It is normally possible to alter the load and horizontal position of a dryer doctor and this is done when necessary to prevent rings of hard scale and dirt forming round the cylinder surface; the trouble with this arrangement is that it is often found that doctors tend to ride on top of rings once they have formed so it can prove very difficult to remove them and at the same time prevent others forming. Any contamination on a cylinder surface affects appreciably the resistance to heat transfer through the surface and is not, especially in the case of the uneven patterns associated with rings, conducive to uniform and efficient drying. Doctors should be adequate to prevent build-up in the first place and their construction, operating load, and the provision of oscillation gear should be carefully considered with a view to finding the best method of keeping all cylinders continually shining without creating an excessive drag on rotation and thereby pushing up the driving load.

Doctors on calenders are of a more elaborate construction designed to ensure an even and relatively light pressure over the full length of the roll, an essential consideration if wear is to be kept uniform. They are manufactured from a variety of materials including carbon and stainless steel, phosphor-bronze, and fibre, the choice being made to compromise rate of wear of the roll against wear of the blade; generally it is preferable to use the softest blade that does an effective job because changing is much cheaper than frequent re-grinding of a calender roll. Dust-extracting equipment combined with the doctors is more common on calender rolls where much fuzz and dust is frequently generated and it is highly important to prevent abrasive materials entering the nips. A quick method of raising each doctor, manually or pneumatically (in which case a single operation can be arranged to raise all doctors simultaneously), is useful to permit cleaning at every opportunity; any pieces of grit wedged between the calender roll and doctor can rapidly lead to wear and scoring. Pneumatic loading is beneficial in preference to spring tension as it permits a readily-controlled pressure of contact, usually of between 1 and 2 lbs. per linear inch. The angle of each doctor also requires careful setting and should

remain relatively unaffected by wear; also oscillation is particularly important for calender doctors. The bulk of the doctor frame frequently takes up enough room to act as an effective nip guard—a valuable asset.

5B.10 3 Felt and other equipment

Each dry felt requires a stretch mechanism (generally allowing a movement equivalent to about 10 per cent. of the length of the felt) and this serves also to apply the required running tension to the felt. On very old machines the necessary stretch and tension may be achieved simply by positioning the roll according to the dryerman's judgement, but this system is far from satisfactory because of the rapid dimensional changes which can occur particularly in cotton and wool dry felts at a break. A more common method of applying an even tension under all conditions involves the use of weights which can move up or down, on a frame situated at the back side of the machine, in accordance with movement of the stretch roll. However, on modern fast machines such weighting gear is cumbersome and it is becoming more usual for the desired tension to be applied by means of hydraulic pressure acting through pistons on both journals of the felt stretch roll. This permits the tension to be accurately indicated and set to any desired value, and it is also possible to arrange for tension to be automatically relieved at a break to prevent straining a felt when it is liable to shrink.

Various types of guide for felts are in use and nowadays these are always automatic, though the old, purely manual adjustment is still retained on one roll of each felt partly as a precaution against failure of the automatic guide but also to allow some adjustment which permits the guide to be set working centrally. Automatic guides in general use for many years include the spade-actuated and drum or cone-roll type, while more modern devices detect the edge of the felt by means of air jets or a photo-electric system. Correction of the position of the guide roll requires (except for the cone-roll system) some motive power, and air or fluid pressure on an appropriate diaphragm or piston is commonly used for this purpose. The self-actuating servo-roll is also coming into more general use for dry felts which do not alter greatly in dimension, particularly the plastic-wire type and synthetic felts.

Expanding spreader rolls with a fixed or variable bow are sometimes used on the web in the drying section to regulate cross-direction shrinkage, but normal application is between the dryers and calenders, and between the calenders and reel-up. In these positions they help keep the web spread out over what is frequently a long pull, avoiding (especially at the edges) wrinkles and creases in the calenders (which produce cuts in the paper) and in the machine roll. An alternative is to have a simple bowed bar or 'spreader' bar: the advantage of this is that construction and support of the bar can be readily designed to allow slight alterations to the bow anywhere along its length according to conditions; the disadvantage is that the hard friction between web and bar generates dust and can in some cases damage the surface of the paper.

In the position between the dryers and calenders it is good practice to use

490

a spring or dancing roll which moves gently up and down on springs according to the tension in the web; this effectively damps fluctuations in draw between these two sections where, because of the varying load that may be experienced on dryers and calenders during running, small variations are common.

Disposal of broke at the dry-end is made much simpler when a broke breaker or pulper is located in a convenient position; this is arranged so that the full sheet can fall into the pulper from both the last cylinder and the calenders. Operation of the pulper is generally automatic in that one or more diluting deluge showers (normally whitewater) are immediately turned on when there is a dry-end break (where there are two showers, one for broke from the calenders and one from a size press, a more elaborate break detection system can be used to select the shower needed). Sometimes the shower can also be turned on manually when other broke torn off the machine roll or trimmed at the winder requires disposal, but it is preferable if a consistency regulator is incorporated either in a small recirculation line or direct in the main line leading from the pulper, and the signal from this is used to control water dilution. Level control is essential and is designed either to regulate a valve opening or to switch on the emptying pump intermittently; in addition rotation of the pulper motor can be arranged to idle when outward flow reaches some pre-set minimum, thus avoiding over-disintegration.

Finally, in the drying section it is often useful, and on faster machines imperative, to have some form of break detector system. Normally this is either photo-electric or ultrasonic in operation (the latter is claimed to have advantages in that it is less affected by dust or dirt and there is no lens system to keep clean); there can be several individual detectors situated down the drying section to ensure as rapid response as possible, and each detector can be arranged to actuate different parts of the system. Detection of a break in this way can be used for a variety of purposes, depending in some cases on the location of the break; these include giving an audible warning, starting a broke conveyor or screw on the presses, sending across the cutter on the wire, reducing steam pressure in the main supply, and starting a deluge shower either on the wire or in a dry-end pulper. In the latter case a selective detector system can be used to switch on one or other shower (normally it would not be desirable to have both on together particularly when the supply is from high-pressure white-water) and a further provision would ensure that the wire deluge shower switch could be manually overridden in an emergency to prevent damage to the wire. Numerous other devices can be actuated by a break-detector system and have been mentioned in the relevant context; many are now considered essential safeguards on any machine.

5B.10 4 The reel-up

Except when a size or coating press together with more dryers are arranged to follow the calenders (or part of the drying section), the sheet passes straight from the calenders to the reel-up. With the old direct spindle drive reel-up it is difficult to apply an even tension as the reel builds up and

491

pressure has to be altered on a belt or clutch to allow for the growing rotational momentum. Also this type of reel-up does not lend itself to easy changing and would be quite impossible to use satisfactorily at machine speeds much above 500 feet per minute or so. At one time it was not uncommon for the same stand to be used for unwinding on the slitter but this practice, never satisfactory because of the congestion it created, is now obsolete.

Various types of drum reel-up are now in general use and, though they differ in design and ease of operation, they invariably permit much more evenly-wound and straighter rolls to be built up. Partly this is because tensions are higher than with the direct-drive reel-up, but also it is easier with this method to keep reeling tightness (governed by the pressure of contact between roll and drum) relatively steady as the roll builds up. The most common type of drum reel-up achieves this by reeling not at the top of the drum but at an angle to it; the full weight of the roll does not then fall on the drum, creating a proportional rise in reeling pressure, but is offset by a gradually increasing angle to the vertical which causes the greater part of the increase in weight to be borne by the reel-up arms. On modern fast machines it is becoming increasingly common to reel horizontally on the drum, keeping the pressure at the reeling line constant by applying an appropriate pneumatic or hydraulic loading to the spindle journals; larger sizes of rolls are possible with this technique. Water is commonly used to keep the drum reeling temperature of the paper cooler, and this also appears to reduce tendencies towards the development of static. A doctor on the drum is needed to prevent the sheet wrapping round in the event of a break.

Change-over of rolls is more or less automatic on most machines with a second spindle ready to be accelerated up to speed on the drum when the existing roll is ready to be removed. The completed roll is edged away from the drum and a blast of air, aided sometimes by a squirt of water, ensures that the paper begins to wrap round the new spindle; it is more satisfactory when this can be done without having to lift the completed roll clear with the crane. A braking mechanism on the old spindle journal to ensure that rotation of the completed roll ceases rapidly is a valuable safety measure. The Pope-type reel-up allowing the spindle to be passed from one set of arms to the other is always preferable to the type which necessitates alternate use of two individual pairs, because one change-over is then clumsier than the other and when reeling on the back arms it can be awkward for the dryerman to check the rolls.

5B.10 5 Special equipment

Equipment of a more specialized nature in frequent use in the drying section can be divided into two broad categories: in one the purpose is primarily to achieve greater smoothness of the paper surface (the breaker stack and smoothing press); in the other it is to increase the moisture content at the machine roll (the sweat roll, spray damper, calender water boxes, etc.). Of course, other specialized devices, such as size and coating presses, are also found in the drying section but these, strictly speaking, are

employed only to add some new specific property to the paper, not to enhance the existing properties; discussion of the use of such equipment is beyond the scope of this work.

The breaker stack is used in the drying section either immediately after the presses or more commonly well down the dryer section. It consists of two highly polished steel or chrome-plated rolls, loaded to give pressure and sometimes steam or hot-water heated, and is thought to serve two main purposes. In the first place the breaker stack effectively smooths out fibre clumps and felt mark on the web surface, giving a more uniform finish and reducing two-sidedness; at the same time the stack seems to help bind surface fibres closer together reducing the extent to which fibre dust and pick-off occurs at the calenders (of particular benefit for offset-litho papers where surface dust readily contaminates the printing blanket). Secondly, it allows more control over the eventual thickness of the sheet (the breaker stack is especially popular for paperboard machines); the overall effect, as may be expected, is to reduce bulk and increase smoothness though it is claimed that the same smoothness can be achieved for less loss of bulk, a big advantage for ordinary printing papers. Because the web is still appreciably damp, the pressure applied at a breaker stack is much lower than at the calenders; but small changes in the load have a relatively greater effect on the finished properties and an accurate indication of this load is absolutely essential to successful and consistent operation. Efficient doctors are needed on both rolls as any grit or crumbs mark the sheet much more readily than at the calenders: feed ropes pass through just outside the edge of the nip.

On any machine equipped with a breaker stack it is important to determine how much of the smoothness eventually required is contributed by the breaker stack and how much by the calenders. A high load on the breaker stack may compact the web to a degree which affects subsequent drying, raising steam costs, while spare loading capacity at the calenders is unused; generally speaking, provided the breaker stack is run at a pressure sufficient to serve its primary function of achieving greater surface uniformity and removing felt marks, there seems little point in raising the load any higher.

The smoothing press is similar to the breaker stack in purpose with particular emphasis on the removal of wire and felt marks in better quality papers. The term is generally confined to the use of a pair of rolls immediately after the main press section and before the dryers though some applications have also been reported in the middle of the drying section. As the name implies, the smoothing press is essentially the same as an ordinary plain press as regards loading arrangements (a lighter pressure is of course necessary), doctors, drive, etc.; the only difference is that no felt is used in the nip and no water is expressed from the web. One of the rolls (generally the top) is rubber-covered, the other usually bronze. If required an embossed pattern of a relatively crude nature can be transferred from the rubber roll to the paper surface at this position, though this technique is usually applied with a separate rubber roll running on the paper web between the last press and dryers. Apart from this the smoothing

press serves only to reduce small scale unevenness in the paper surface on both sides.

The most common method of increasing moisture in the finished paper is by means of the sweat roll, which is always the last roll in the drying section. A supply of cold water is sprayed into the roll and removed at the back journal by a syphon and ejector; this promotes the continuous formation of condensation on the cylinder surface which is then transferred to the paper. In addition, steam may be sprayed on to the outer surface of the roll to increase the condensation rate, and this affords a rough means of varying the effect across the machine. The diameter of the sweat roll must be 50 or more thou. greater at ambient temperature than that of the drying cylinder it follows in order to allow for the expansion of the latter during operation. The need to build up a film of water on the roll surface makes it impossible to have any doctor permanently in contact, so to ensure that paper does not wrap round the cylinder in the event of a break a doctor has to be held ready for immediate application to the surface; the doctor is released when a signal is received from a break detector or (and this is probably more effective if it is made sufficiently rapid) the operation is made automatic by means of a mechanical connection from a spring roll situated between the sweat roll and the calenders (this roll falling to a new position when the web snaps).

The purpose of using a sweat roll should be clearly borne in mind: it is to add moisture into the paper, both to permit reeling closer to the eventual equilibrium condition in atmosphere and to attain a better finish in the calenders. The reason that this is not so easy to accomplish direct off the machine is largely tied up with the difficulty of attaining simultaneously a moisture profile which is both high and uniform, a topic fully discussed in 5C.3; but it is self-evident that the greater the moisture content at which it is possible to reel without the sweat roll, the less steam will be needed to dry the paper out. It is a common failing when operating a sweat roll that it becomes used on a machine purely as a means of cloaking irregularities in profile that ought to be corrected. If the cost of doing this were better appreciated, then perhaps more effort would be made to produce a reel at a reasonably higher moisture content in the first place, and only later start using the sweat roll when a high average proves impossible to achieve without it. Turning off a sweat roll, but at the same time keeping the average moisture level at the reel-up unaltered by adjusting the steam controller according to a moisture meter reading, can sometimes enable the steam pressure needed for drying to be reduced by 2 to 3 p.s.i. with no noticeable increase in the effort required to build up an even roll. There is also evidence that the smoothness of paper increases by a small amount when moisture is retained in the body of the sheet instead of being added at the sweat roll. In this respect it may be noted that laboratory studies reported by Jackson and Ekström (104) have indicated that it is inadvisable to overdry the sheet surface, even if it is re-moistened at a later stage, otherwise the fibres became hard and less compressible in the calenders.

Other devices have been developed with the same intention as the sweat roll of adding moisture to the web. These include: felt-covered rolls dipping

into a water trough and transferring water direct to the paper surface; various types of spray dampers in which a large number of very small water jets impinge direct on to the web, or at an angle on to a plate thereby creating a mist either close to the web or on a roll which the web contacts; rotating brush dampers which also pick up water from a trough, then strike a doctor which scatters a mist on to the paper surface; carefully designed steam sprays positioned close to the nips of calender rolls; and water doctors on the calenders. No objective assessment of their comparative performance is available, though it is obvious that operation will be better the more control there is on the actual moisture picked up both in total and at different points across the web. From this point of view spray dampers and certain types of calender water doctors are probably most adaptable. This applies especially to the former because the flow to individual nozzles can be controlled, or careful choice of the nozzle sizes at different positions across the machine can allow relatively permanent discrepancies in the moisture profile to be corrected, e.g. slightly larger nozzles towards the edges of the sheet compensate for the common tendency towards being dry. Much development has taken place in the construction of non-clogging nozzles of very fine aperture which are designed to give a mist for direct use, and those working on the air-injector principle with compressed air and water lines regulated by separate valves are claimed to give a very uniform dispersion. Water for spray dampers must be well filtered, otherwise the fine sprays clog, while a better mist is possible when the water is hot; increased efficiency has also been claimed for a device which applies a very high-tension d.c. voltage between the spray nozzles and a backing roll, though this naturally involves careful caging-in of the equipment and is unlikely to find general acceptance. Calender water doctors on the other hand need to be of rigid construction to give even application; they should have an easily adjusted overflow head and be mounted perfectly level.

Several of these devices are used after the calenders, for example a spray damper to apply water to the reel-up drum. The main purpose then is to raise the moisture level to improve subsequent supercalendering. But no matter where or how moisture is added, the same general comments on the practice apply as when using a sweat roll, and ample caution is needed to prevent addition of water exceeding the level that is absolutely necessary. In all cases of direct application some measure of the water being applied is highly desirable and should be used to check excesses. Whenever possible it is also desirable to measure the web moisture content before the application of water, especially of course when the reading is used to regulate drying. Neither of these controls is available in the case of a sweat roll and in fact it is not possible, other than by using an elaborate moisture meter set-up or regularly breaking down the sheet to obtain moisture samples, to keep much check at all on how the roll is functioning.

A more recent addition to devices available for adding moisture is an on-machine conditioner using high-velocity, high-humidity air blown on to the paper from nozzles (121). The web is supported on wire-wound drums and the whole device is hooded to give closer control of operating

conditions. It is claimed that in addition to allowing moisture to be added to the web, the cross-machine profile is also improved.

Finally, to complete this brief description of more specialized equipment a short note on static eliminators is called for. The need to reduce static at the reel-up when this reaches unpleasant proportions has called forth a wonderful variety of contraptions most of which, it is certain, do anything but what they are intended for. The most popular comprise chains or strips or tufts or bristles of copper wire suspended at judicious intervals across the machine immediately after the calenders. These wires are carried on a bar, lowered to a position where they just touch the web, and are connected to a cable sufficiently thick to conduct a stroke of lightning away to some mysterious and inaccessible point carefully selected by the electricians. In theory static electricity is seduced from the web by this attractive array of whiskers and led away to an obscure and anonymous fate in the bowels of the earth. Gazing at a typical static eliminator one can easily visualize that electricity is flowing along the wire, and the occasional spark re-inforces the certainty that static is indeed being eliminated. It is then hardly comprehensible that, having recklessly abandoned the precaution of wearing rubber-soled boots, a gentle touch of the roll with moist fingers indicates by the strength of the kick that some static has surprisingly slipped through the net.

All that can be said on this topic is that as yet no certain cure exists for static. One of the difficulties is to get a satisfactory measure of how much static is present, though a convenient hand instrument is available which is calculated, by its shape, to cause concern to any dryerman and is well worth using for this reason alone. Static is less alarming on the machine roll the damper the web is reeled, and once present in paper it disperses easier the drier the atmosphere; a water-cooled drum reel-up quite definitely helps. Static can be extremely troublesome when cutting into sheets and laying down. But the greatest difficulty is the complaints the consumer makes, particularly the printer using sheets. Especially for his sake it is best to retain your own personal brand of eliminator in a prominent place on the machine.

CHAPTER 5C

RUNNING THE DRYERS AND CALENDERS

5C.1 DAILY OPERATION

In dealing with various aspects of running the drying section and calenders, the same procedure is now used as for earlier sections of the Fourdrinier. Measurements required by the machine crews for day-to-day operation are discussed first, and this is followed by a detailed consideration of the longer-term maintenance necessary to keep up efficiency. Two features of the dryerman's work that command especial attention, those of keeping the moisture content and thickness of the web at the reel-up steady and also uniform across the width of the machine, will, because of their importance, be dealt with separately. Finally, there is a general discussion covering practical points.

5C.1 1 Essential measurements

During normal everyday running, conditions in the drying cylinders are closely characterized by the temperature or pressure of the steam supplied to the main bank; if anything goes seriously wrong in the operation of the dryers it is almost certain to be reflected one way or another in the steam required for drying. Fluctuations in demand produced by varying moisture content of the web entering the cylinder section are also reflected in the steam pressure, as are variations in the boiler pass-out supply in an uncontrolled system. On many machines drying pressure is close to the maximum available and indication of this is vital. For these reasons, and many others discussed earlier, a measure of the temperature or pressure of the steam supply is absolutely essential for the dryerman, and only a record rather than a straightforward indication can ensure that full use is made of this. An alternative is to measure steam condition in a selected cylinder or temperature of the condensate, but either of these methods introduces condensing variables and is unlikely to be so effective particularly when used for control purposes.

Steam supplied to the main bank and throughout the cylinder section is normally saturated, so either temperature or pressure may be taken as an indication of its condition. This, however, applies only provided adequate precautions are taken to avoid air in the cylinders; with a significant proportion of air present, pressure does not indicate the relevant property of the steam which controls the drying rate and strictly speaking only temperature is appropriate for this purpose. A temperature measurement using a bulb in the main supply pipeline and a filled thermal system to the recorder is simplest, but this method is relatively insensitive to the small changes in condition that it is important to be able to observe. This is particularly the case at higher steam pressures such as are used on M.G.

497

and very fast machines; in these cases pressure is almost always the characteristic measured, because the temperature change corresponding to a given increase in pressure becomes gradually smaller the higher the pressure. Pressure measurement using a direct connection-tube from the pipeline is not satisfactory because the pipe is normally situated at the back side of the machine and so either the recorder must also be sited at the back where it cannot readily be seen, or precautions have to be taken to ensure that varying condensation in a long connection-tube over to the front side of the machine does not affect the reading. A slack diaphragm with enclosed air or liquid connecting-tube to the recorder is a better arrangement, but the most suitable and sensitive (and the most expensive) system is to install a pressure transmitting device using a standard air-pressure signal to the most convenient position to display the record; this arrangement is readily adapted for control purposes, a facility which is particularly advantageous.

In addition to the main supply steam pressure, numerous other lines must have at least a gauge to display the relevant steam pressure. The positions where such measurements are taken depends entirely on the lay-out of the system, but obviously include the steam supply to such parts as the felt dryers, calenders, and air-heaters; separate pressure measurements are necessary for each bank of cylinders on a flash system or when sections are taken separately off the main steam supply, as for example when using differential drying for top and bottom cylinders, or an M.G. cylinder and pre- or after-dryers, or a thermocompressor system. In addition, pressure measurements upstream of the main steam control valve, in condensate lines or flash tanks, and on the final condenser are required; when any individual cylinder is throttled separate gauges on inlet and condensate lines or a differential pressure gauge are advisable. In more modern installations differential pressure measurements giving the pressure drop over each section in which steam is used are common, though these are normally associated with control systems which are discussed in 5C.14. In certain cases it is well worthwhile to use recorders rather than simple gauges. For instance, a useful arrangement is to use the same recorder for both main steam pressure and the pressure of the first flash-steam line; this enables the condition of the most important part of the flash system to be watched, together with the total differential held over the main bank plus any controlling valves in the main condensate and flash lines.

There are a number of other measurements which are essential to efficient operation of the dryers and calenders. The load applied at the calenders, breaker stack, smoothing press or, in the case of an M.G., at the pressure roll must be displayed on a double-gauge system, one showing the load at the front and one at the back; in general, the same type of instruments as were described when dealing with the presses are suitable to measure the load in each of these cases. The use of the gauges is also very similar to their use in the press section: in particular, they are essential to set the load to the desired level and examine how variations in the load affect performance, though for these applications of course the effect of a

given load is assessed essentially in regard to the smoothness of the paper rather than the water removed. Further, the importance of the measurement in its relationship to the camber of rolls and cross-web uniformity is , also exactly as for the presses and as the same principles apply in each case, the value of load measurement in this respect has also been covered in the earlier discussion of the subject; the only major difference lies in the operation and maintenance of the calenders to give a uniform smoothness across the machine, and this is dealt with later in 5C.4.

Whenever possible, the power consumed by each individual section in the dryers, and by the calenders and reel-up, should be displayed on ammeters. These should preferably be equipped with a limit warning which immediately draws the dryerman's attention to excessive demand at any part of the machine under his supervision. This warning device is of particular value in indicating instability and disturbances in the cylinders due to varying condensate volumes, but also allows early attention to be given to any conditions (heavy doctoring, excessive draws, tight felts, stiff bearings, etc.) which may affect the power usage adversely. For the same reason, and to give indications of adverse trends, a log of the power used by each section should be completed at specific intervals; the same applies of course to the power consumed by the whole machine as this information is required for accounting purposes.

Another essential measurement is of the water flowing into any damping device before the calenders or reel-up. Especially when using sprays, a pressure gauge is not really adequate in this position because any change in the spray orifices, either by design or due to gradual erosion or scaling up, affects the flow even when upstream pressure is kept constant; it is preferable in addition to have a simple indication of flow rate which is used for setting water to the damper in conjunction with the pressure gauge. A table showing the rise in moisture which is roughly equivalent to different flow rates is also useful to have on hand in order to prevent excessive drying down of the sheet before damping.

Certain measurements of air state (primarily temperature and humidity but in some cases also the pressure or flow rate) are essential if ventilation conditions are to be kept under control. This applies particularly to hooded machines where the full value of the hood cannot be realized unless systematic regulation is possible. Usually measurements are taken of the condition of supply air to Grewin systems, felt blowers, high-velocity air hoods, etc. and also of the exhaust air in appropriate places. In many cases, of course, such measurements are part and parcel of the control systems which are a normal feature of any well-designed ventilation system. Each installation is individual to the machine but it is evident that the more elaborate arrangements permitting close control and fine manipulation of air conditions in different parts of the dryers, as indeed of the machine house, are generally worthwhile economically because they show how the heat supply can be reduced and heat wastage minimized. Even the oldest machine may well benefit from placing one or two wet and dry bulb thermometers in key positions in the machine house and noting how their reading changes under different operating conditions.

Finally, for production control purposes it is absolutely essential for each machine to be equipped with some form of recorder which can be used for analysing downtime. This should preferably give a complete record of when paper was being made on the machine, and so requires a device (feeler arm, photoelectric cell or ultrasonic signal, tension bar, etc.) which senses when the sheet is passing through to the reel-up but is not affected by normal reel changes. The record may be a straightforward one on an appropriate time scale showing, for example, the start-up time, various breaks which occurred during the week or between scheduled shuts, and shut-down time. Or, and this is the author's own preference, such a breaks record can be combined with a speed record in order to allow ready analysis of machine performance at appropriate time intervals. Together with an arrangement of this type can be associated integrating clocks to show time lost during specific periods, and more elaborate arrangements are possible which distinguish between dry and wet-end breaks and even integrate time lost due to different causes. The use of such data in conjunction with machine reports is of great importance to the production personnel, the accounting department, and management: this will be fully discussed in Part 6.

5C.1 2 Useful measurements

Other measurements which can with value be made available to the dryer-man include flows of steam and condensate, the draws and sheet tension, felt tension, and (depending on the reel-up design) the pressure of the machine roll on the reel-up drum.

To obtain full value from their use, steam flow meters are necessary in the supply lines to each separate part of the drying system; this means having individual meters on the main supply to the drying cylinders, on an M.G. cylinder, felt dryers, hoods (especially H.V.), and the machine house ventilation system. In each case a straightforward orifice system of measurement is adequate, certainly for comparative purposes, provided upstream supply pressure is reasonably controlled; it is beneficial always to install recorders and integrators at each position though the same recorder can frequently be used to chart two or more different pressure readings. Such equipment serves two main purposes. In the first place it provides useful data for cost accounting without which in a multi-machine mill only very crude estimates of operating steam costs are possible. Secondly, the effect of changes in clothing and other operating conditions can be studied with a closer knowledge of the steam costs involved. Attention has already been drawn in this respect to the fact that the main dryer or M.G. steam pressure found necessary to dry the paper to a given moisture content does not of itself necessarily alter in accordance with the actual quantity of steam being used: it is quite possible for a rise in the main steam pressure used for drying to be associated with a drop in the quantity of steam used. To assess the full effect of any change to the drying section both pressure and flow measurements are necessary. The same applies to the steam used in felt dryers, hoods, or the machine house ventilation system, though for these positions the use of steam flow measurement is essentially to compare

the effect of changes in operating conditions, e.g. in the felt dryer pressure or the temperature of a Grewin or H.V. hood air-system, on the comparative steam flow rate to the equipment concerned as opposed to the drying cylinders; on modern machines the steam used to heat air in hoods can represent a third of the total heat consumed by the drying section and so obviously requires careful setting. Without flow meters on the various steam lines to each separate part of the system, it is hardly possible to assess the effects of changing operating conditions sufficiently accurately; a single flow meter measuring the total steam used on a machine is a cheaper substitute, but is rarely satisfactory because some steam is likely to be supplied at a higher pressure than the main dryer steam and also because a single measurement will permit only relatively large changes in total flow to be detected.

Measuring the flow of condensate from a machine is also important. This reading, especially when integrated over a suitable period, can be compared to a similar reading from a steam flow meter and thereby indicate losses occurring in the system (important for reducing steam wastage and because after de-oiling condensate water is more suitable and cheaper than fresh water for re-use in the boilers); it also provides a useful check on accuracy of the two instruments. This function of providing a check on the accuracy of flow measurement also applies from the point of view of the boiler-house unit, where water entering from condensate lines together with that from returned low-pressure steam and from fresh water sources can be balanced against a measurement of the total water entering the boilers, a highly important piece of information for assessing boiler operation. Finally, when used in conjunction with a recorder, the overall stability of condensate flow can be examined and this provides useful information on how well the machine drying section, especially in a cascade system, is functioning: surges in condensate flow can be surprisingly large and may be a direct consequence of poor operation (water-logging of cylinders, temporary blockage, faulty traps, etc.) that is difficult to detect in other ways.

The purpose of draw indicators between each section of the dryers, calenders, and reel-up is basically the same as that already discussed with reference to the couch and presses. They are valuable for pre-setting draws (especially when crêping) and thereby remove a frequent source of trouble in feeding-up; also alterations to the draw found necessary to operate satisfactorily give an indication of the composition and structure of the sheet. In the dryers, draw indicators are of most use when associated with sheet tension measurements between the sections. This is because it is essentially by the tension in the web that the draw is set. Tension can be measured in several ways and the most popular is to use a full-width roll acting either against springs, the positions of which at any time give a measure of tension, or against appropriate strain gauges in the journal supports; the latter arrangement is often used in conjunction with draw controllers (see 5C.1 4). Setting web tension between the different sections is especially important when manufacturing a paper with closely-specified stretch properties, but on any machine facilities for keeping the tension at a

low value are valuable for avoiding creasing, quality variation, and breaks caused by overstraining the web.

Felt tension devices which rely solely on positioning a stretch roll are far from satisfactory because there is no means of judging (except crudely) at what tension a felt is running. With such equipment some method of measuring felt tension (similar to those used for measuring web tension) provides a most valuable indication of running conditions; for this purpose a simple spring-supported roll with a lever to magnify movement is an inexpensive though adequate means of giving a qualitative indication. The tensioning arrangement which involves the use of weights sliding on a vertical carriage improves considerably on the simple stretch roll, and the weights in use on any felt are normally rarely altered so that in effect felts are always kept at the same tension. Measurement of felt tension is useful (and readily available) in association with a pneumatic or hydraulic loading system on the stretch roll and this permits running tension to be set and altered as desired; in particular, automatic slackening of felt tension at a break is possible.

The pressure applied by the machine roll on to the winding roll of a drum reel-up can usually be varied either mechanically by weighting the lever arms or by means of special pneumatic or hydraulic loading cylinders. Whatever the system an indication of this load should enable the dryerman to produce a roll to a more uniform hardness especially when, as is generally the case, the load has to be altered anyway as the roll grows to take care of the changing pressure on the drum.

5C.13 Dry-end paper quality instrumentation

Several instruments have been designed for the continuous measurement at the dry-end of various properties of the finished sheet. These include substance (dealt with in Part 1), moisture and thickness (discussed separately in 5C.3 and 5C.4), formation (see also Part 3), and gloss, opacity, colour, air permeability, and edge-of-web curl; in most cases the instruments are available commercially and can where appropriate be arranged to traverse across the web. There are also devices which scan the sheet for dirt specks (using an optical transmission system) and for the presence of holes and wrinkles (this can be done either with electrical feelers, or using optical methods or ultra-violet light). This whole group of what may be termed 'quality' instruments will now be considered in broad terms; the value and operation of individual instruments will not be discussed because their importance and possibilities depend closely on the particular paper being manufactured.

To begin with it is worth stressing that no advantage is gained from measuring any property of the sheet continuously for its own sake. Substance, moisture and thickness are important basic properties of any paper and can readily be adjusted or automatically controlled (along if not across the machine) to enable a more consistent product to be turned out; for these reasons a strong case can be made out for the continuous measurement of these particular properties at the dry-end. In addition, other characteristics of a paper almost always depend in some way on substance,

moisture and thickness, so these should first be under reasonable control before venturing into further quality instrumentation. Once this is achieved it may well be discovered that any changes in other properties, formation, opacity and so forth, are relatively slow to occur; in this event it must seriously be questioned whether the alternative of a quality (or process) control system involving the testing of samples taken from each machine roll may not provide adequate information and in the long run be simpler to operate.

Generally, whenever a quality instrument is installed at the dry-end and found to function reasonably well one of the earliest tasks is to try to set up some sort of control system. The pitfalls inherent in this have been well documented by MacLaurin (63) who has illustrated the important but neglected point that no control system is adequate unless it controls the right variable: he cites an instance where control of opacity by addition of titanium dioxide proved extremely expensive compared to making other less easily controlled alterations of preparation conditions which could achieve the same end. All qualities such as air permeability, curl, formation, gloss, and so on are affected by numerous variables on the machine. The alterations which are practicably possible and which lend themselves to being coupled up to some form of control system are often not the ones which have most effect on the property in question. Difficulties with excessive time-lags in the system also occur. Hence control can be difficult, or at worst damped to such a degree as to be virtually ineffective.

A better approach to the problem of general quality variation may well be to improve overall machine instrumentation and control a greater number of characteristics right through the system. With carefully documented data showing as comprehensively as possible the operating conditions during the making of each grade, and with a well-run quality control system checking the performance, it should be possible to keep quality consistent both within and between different makings. The main shortcoming of relying solely on this general method of achieving greater product consistency is the difficulty of experimenting to improve or alter the paper quality in some way. Sometimes a relatively long-term statistical method such as Evolutionary Operation can be resorted to because this does not require changes in operation which are immediately evident. Otherwise production time has to be sacrificed in order to make it possible to use the classic techniques of experimentation which, to yield useful results, require adjustments to the process of an order that result in readily detectable alterations and so almost always involve the making of some paper that is out of quality specification. Continuously-measuring quality instruments can provide a valuable function by allowing the effect of small operational alterations to be observed more readily, thus giving information which must otherwise be obtained more laboriously. But for this purpose it can be argued that only an experimental unit is necessary, a topic beyond the scope of the present discussion.

It is also worth pointing out that even the use of continuously-measuring instruments to enlarge knowledge of the system may in time be superseded by the advent of 'on-line' data-logging computers which incorporate

quality control results with routine data from machine instruments. One of the prime values of such computer installations is likely to be their facility for mathematical model building which will enable the effect of all the measured operational variables on each aspect of quality to be effortlessly isolated, leading to a clearer recognition of what is involved in keeping each property uniform; following on this it is possible to envisage automatic optimization of each important property (taking care even of uncontrollable environmental changes) by use of a systematic procedure for altering the set-points of each controller on the machine and searching for the positions giving the best overall result. Such a system, the ultimate in automation, is, of course, very much a pipe-dream at the moment so far as the paper machine is concerned.

Quality instrumentation at the dry-end almost always requires very careful standardizing and frequent attention if it is to be kept at an operational level which is sufficiently useful to be relied on; it is also not always easy to check how the properties actually measured by the instrument compare with those which it is desired to measure, particularly with regard to subjective qualities where laboratory instruments can more readily be compared with subjective assessments by carefully controlled ranking tests. In the case of devices such as dirt counters and hole detectors it is arguable whether the machine dry-end is the best place for them anyway. The main use of this type of equipment is in automatically sorting out paper which must be rejected because it is below the acceptable quality level required; on the paper machine itself this function is hardly suitable unless it is thought practicable to have tabs inserted in the roll according to the dirt-level, number of holes, etc., registered in a given time. The only advantage in using such devices actually on the machine would seem to be the quick availability of information about deteriorating conditions which would enable rapid steps for correction to be taken. Probably the winder taking machine rolls immediately after they are thrown out is the best position to compromise the two functions of rejection indicator and early warning system.

Normally any quality instrumentation has to be installed between the calenders and reel-up in order to measure the appropriate paper property in the condition most closely approximating to the finished, saleable product. The result is that especially when measuring systems with cross-web traversing facilities are required the available space between calenders and reel-up can easily become cluttered with arms and beams, switches and terminal boxes. This is hardly likely to endear the devices to the dryerman, particularly when he finds it difficult to feed up the sheet without injuring his rear or his head on some projecting piece of hardware. But specialized forms of 'quality' instrumentation are continually growing in scope and value so some means must be found to accommodate equipment that will eventually be considered vital to successful operation. As most of it is electrical or electronic in operation, and is generally sensitive to dust, ambient air eddies, and sharp knocks (intentional or otherwise), it seems likely that a large box will eventually be found necessary to enclose all the various instruments; this box would stretch across the full-width of the

machine, with a slit for feeding into from the calenders and appropriately placed air blowers to lead the tail from an outgoing slit on to the reel-up—it would, of course, be painted black.

5C.14 Control applications

There are a number of control systems often associated with the drying section, of which the most important involve control of the supply steam pressure (with developments from this), and various aspects of drying cylinder and hood (ordinary and H.V.) operation. Control of pressure of the steam supply to the drying cylinders and other parts of the machine has been found extremely effective in probably all cases where it has been installed. The control is arranged quite simply by using a pressure or temperature signal from the main supply line (see 5C.11) to adjust the position of the main valve; even when up-stream pressure control is very good the changes in steam demand at a given pressure require that an integral or reset action be incorporated in the controller to avoid offset, a condition in which the actual pressure controlled at differs from that desired.

The main advantage of this simple steam pressure-control system is that it reduces fluctuations in the drying which manifest themselves at the machine roll by sudden and erratic periods of dampness, perhaps associated with blackening or creases. This in turn permits a higher average moisture content to be attained with all the advantages this carries. With M.G. cylinders, where the temperature must be raised gradually at start-up to avoid stressing the metal, a normal steam control system is readily adapted to ensure a regulated rate of introduction of steam during heating-up. As with most control systems, the position of the steam control valve should be shown on the same recorder as the actual steam pressure to permit operation of the system to be examined. Link-up with moisture meters to provide a more elaborate control taking account of variations in conditions affecting the rate of drying, e.g. moisture content of the web entering the cylinders and ventilation conditions, is discussed in 5C.3.

Other control systems associated directly with the drying cylinders and with hoods are becoming more common and increasingly elaborate; most have already been described in the appropriate context and will be mentioned here only briefly. Control of drying cylinder operation usually depends on ensuring that the differential pressure across a bank of dryers remains steady and this can be achieved either by regulating a supply of make-up steam into the flash side, or by adjusting a throttling valve in the condensate or in the flash-steam line; often one or more of these methods is used simultaneously and separate arrangements allowing for the change in conditions at a break can be incorporated. The temperature of steam in any individual section can be controlled exactly as the main supply steam, and it is possible even to have a control giving a pre-set temperature gradient along the first few dryers. Similar arrangements are used for cascade systems, M.G. cylinders, and thermocompressor systems. The level in all condensate receiver tanks is controlled, also the pressure or vacuum in the final receiver (usually by varying the quantity of cooling water

505

injected by spray or circulated through coils). Other control facilities, e.g. automatic venting of flash tanks to keep the air content below a desired minimum, can also be installed.

With ordinary and H.V. hoods control of supply air conditions with respect to any desired temperature and humidity is commonplace; exhaust air conditions can also be controlled, normally to a desired humidity level, by regulating the quantity of air recirculated. The precise manner in which this is achieved depends essentially on the system lay-out, whether heat-exchange equipment is incorporated in the exhaust, and the steam supply available for heating incoming make-up air. Such controls are often considered to be an integral part of the design of any type of hood and are valuable for ensuring successful operation at an economic level.

Two other control applications are occasionally found in the drying section. One is control of the draw from a measurement of web tension, a direct development from having some simple tension measuring arrangement. This control can be achieved either mechanically or electrically, depending very much on the drive system, and due to the sensitivity of draw settings in the dryers can be a valuable facility for reducing breaks.

The other application is control of a dry-end pulper: this involves primarily level control together with, where possible, control of consistency and temperature of the stock also; various methods of achieving this have already been described earlier. The object here is efficient and uniform disintegration of broke to make its introduction back into the preparation plant or machine chest as trouble-free as possible. To this end a useful feature of any dry-end pulper operation is to have a means of reducing the rate of disintegration when little or no broke is entering the pulper; as it is normally preferable to maintain continuous operation if only to be ready for a sudden break at the dry-end, this really precludes the obvious possibility of using the pulper on a batch system, and some arrangement is therefore useful to idle the rotor when the flow-rate from the pulper drops below some pre-set value. Another useful facility is an indication at the dry-end of the main broke tank level: as the supply of dry broke fed back into the system needs to be steady to help maintain uniform preparation conditions, it is evident that the broke tank level must so far as possible be kept between two points, an upper one above which the broke usage needs to be increased to prevent the risk of overflowing the chest and a lower point below which broke usage must be reduced to avoid the possibility of emptying the tank. By having an indication of broke-tank level at the dry-end, especially with an appropriate warning light to show when level is dangerously high, the dryerman is able to regulate addition to the pulper of broke that has been torn off machine rolls or trim from the winders, etc.; also he can keep an eye on the level during a prolonged break at the calenders when the full machine web is falling into the pulper.

5C.2 MAINTENANCE OF THE DRYERS AND CALENDERS

5C.2 1 Felt changing

The changing of dry felts is an essential part of the maintenance of the drying section, though the problems involved in performing this system-

atically are by no means as complicated as for wires and press felts. This is because dry felts invariably last many months on a machine and represent only a few coppers of the cost of producing a ton of paper. Unfortunately, it is perhaps for this very reason that on many machines dry felts are neglected and become an unnecessary source of lost production.

As with other clothing, a record is kept in which the various makes and types of felts used in each position of the dryers are listed, together with their cost and general comments on how well they ran on the machine. In addition there will be some means of comparing the performance of different types of felt, and commonly this will either simply be the life in days or weeks, or the tons made on the machine during the felt life. This sort of information ensures that only suitable felts are used in each position and in the long run assists considerably in discovering the physical make-up, material, and other characteristics of the felt best suited to each particular application.

The weakness of this simple record system, as with press felts, is that it emphasizes the importance of felt life. Other aspects of performance will certainly be taken into account; in particular, systematic records will reduce the possibility of getting felts which are unsuitable for reasons such as shedding of fibres, tendencies to harden or burn, and undue dimensional instability which causes the stretch gear to be strained at a break or necessitates taking a piece out of the felt and re-seaming after a few days on the machine. These points are certainly of importance, and it is most desirable to select felts which require as little attention as possible through-out their life. But especially with dry felts there is absolutely no advantage gained from prolonging running time on the machine excessively. Many papermakers mistakenly pride themselves on the life of their dry felts and will not take one off until it is threadbare and almost in shreds. Certainly there is little evidence that deterioration even to this extent affects the overall drying unduly, particularly in the case of felts used towards the end of the dryers where they play only a relatively small part in the mechanism of drying; but it is nevertheless evident that a policy based on squeezing as many weeks as possible from each dry felt will eventually cost far more in downtime, for repairing unmanageable holes and for un-scheduled shuts when a felt suddenly tears apart, than can possibly be saved in felt costs.

The author favours a system of scheduled changing for dry felts based so far as possible on a regular pattern. With such a procedure, each dry felt is changed after a pre-determined number of weeks and a sequence is devised so that no two felts (particularly the first two) are changed at any one time. The main advantages of this are that it allows better planning of the work involved, enables stores of new felts to be ordered more systematically, and prevents any sudden change in drying conditions arising from having to put two or more new felts on at the same time. Whenever possible the same standard life is chosen for each felt, thus permitting a regular pattern to be formed: for example, it may be decided to run the eight dry felts on a machine for a life of 32 weeks each, so one is changed ever 4 weeks. Accidental damage, trials, or unexpected deterioration will of course throw

the sequence temporarily out of gear, but it is always simple to adjust the changing dates to correct this.

Adoption of a planned changing scheme of this type can mean removing some felts that look far from worn. But it is likely that an old felt does begin to have some adverse effect on drying as it hardens and becomes more impervious with age, even if only in causing some variation in drying across the machine which affects the moisture level of the machine roll and thereby necessitates a reduction in the average moisture content; if this were the case then clearly it may not be uneconomical to remove a felt before it has reached the end of its practicable running life. But leaving this point aside, regular removal somewhat earlier than the former average life invariably pays for itself by reducing to negligible proportions the need for stopping the machine to change or repair unexpectedly.

This is not to say that once planned changing is introduced no further effort is made to improve performance; new types of felt are continually appearing and it is the papermaker's duty to assess their virtues for the machines in his charge. Provided the new felt runs satisfactorily, it would be usual practice to relate the average life to the cost of the felt and so compare the running cost with that for the usual type of felt. In some positions this can mean that certain hard wearing materials, e.g. synthetic re-inforced and terylene, are economically preferable because the extremely long life which they give far outweighs the initial higher cost for the felt. Even when the longer life of such a felt is more or less balanced by its greater expense, reduction of labour charges from changing less frequently and the lower likelihood with slower deterioration of a sudden change being needed make it the preferable choice. But against this, higher storage costs for replacement felts (especially if a felt is individual to one position in which case normally at least two must be kept lest one is damaged when being put on the machine), and the risk of greater loss resulting from accidental damage, means that little advantage is gained by achieving a felt life in excess of one to two years.

5C.2 2 Influence of felts on drying

A feature of dry felt performance which is invariably neglected is the effect on drying rate and steam utilization efficiency. But much evidence has already been given to show how different types of felt alter the drying, and the effect this has on steam costs, or on drying rate when production is limited by restricted drying pressures, is of obvious importance; as an example, a change to a thicker and heavier felt of the same material and weave may well yield a proportionally longer life and be more economical to run, but both drying rate and efficiency could be reduced and this is likely to be far more significant. One reason for the lack of attention devoted to this aspect of dry felts is the complexity of comparing performance, especially on machines making many grades; but the potential saving in this respect is far more important than any gain in reducing felt costs, and no change to a new type of felt should be made without making some attempt to evaluate changes which occur in the drying. The means of doing this will now be discussed.

Carrying out regular dryer tests, as described in 5C.2 4, is the best way to have on hand enough data with which to compare the performance in any particular position of different types of dry felt. Otherwise, for this specific purpose the main information required for each felt is the drying rate through the section concerned and some comparison of overall steam consumption related to water evaporated (see below). The drying rate over the full drying section may give an indication of some change, but where more than four felts are in use it is preferable to take samples for moisture content determination from the middle of the dryers in order to determine the water removed in the particular section concerned; several determinations through the life of the felt are required and so far as possible, to avoid complicating the issue in the absence of other data, these need to be obtained at times when conditions, particularly machine speed, grade of paper, and steam pressure, are nearly the same (this is of course because of the dependence of drying rate on steam pressure and moisture content entering the cylinders).

It must also be remembered that each section usually contains two dry felts and the effect of changing one may be partly masked by the other. One way to avoid this and isolate the effect of an individual felt is to determine the rate of condensate flow from several consecutive top and bottom cylinders in the section concerned (though see 5C.24 for comments on this). The relation between the average flow from cylinders covered by the new felt with those opposite covered by the other felt is then compared with the same relation for the old felt (it is necessary to take a comparative figure in both cases because even with identical felts on both top and bottom cylinders the evaporation rate will not normally be the same due to the influence of ventilation conditions, felt age, felt drying capacity, and so forth): for example, if in one position on a machine a new type of top felt is tried, an improvement in drying rate should be indicated by an increase in the ratio between the average condensate flow from two or three of the top cylinders and the average flow from the adjacent bottom cylinders (still covered it is presumed by the same felt as before). Alternatively, samples of the web for moisture content determinations can be obtained from between several consecutive cylinders and used to calculate the water evaporated by each cylinder, the data being used for comparative purposes in exactly the same way. The difficulty with this method is devising a satisfactory sampling technique (see 5C.2 4).

It may be argued that a change in drying rate, to be really significant, should be readily apparent from the change in steam pressure needed to dry the paper under normal operating conditions. This is perfectly true, though it is always preferable to have more systematic data on which to base a decision as to the effect of any particular felt on the overall drying rate. It is after all a rare occurrence when the substitution of a new felt makes a difference to the drying rate which is immediately obvious.

The other aspect of felt performance which can be of importance relates to the efficiency of steam utilization. As steam flow is never measured to individual felt sections the only means of assessing any change of this nature is by relying on data for the total steam flow to the whole dryer

section and relating this to the water evaporated. This can be done by comparing results obtained in a number of tests on both old and new felts, in each case using a steam flow meter and sampling the web for moisture determination entering and leaving the dryers. Alternatively, where a machine makes virtually the same grade all the time, over a number of weeks a significant change may be detected in the ratio of the total steam used in the dryers to the total paper dried (provided downtime does not vary greatly).

5C.2 3 Other maintenance

Apart from the dry felts, there are several other parts of the drying section that require regular inspection and maintenance. Sheehan feed ropes can cause a surprising amount of downtime if insufficient supervision is given to their operation. As an item of relatively small cost it is far preferable that ropes are changed at frequent fixed intervals chosen to reduce to negligible proportions any attention to them which necessitates stopping the machine. In between changes the ropes should be regularly inspected for signs of fraying and loosening splices, and the tension gear should also be checked for free movement; cross-over points in particular must be set carefully. A record of the life of ropes in each position is essential to show up excessive wear due to sticking or misalignment of pulleys, rubbing on the frame or other ropes, and so forth.

The outer surfaces of drying cylinders and M.G. cylinders, especially the latter, should be kept as bright and polished as possible and if the polish cannot be maintained satisfactorily while the machine is running then periodically the surfaces (particularly of the wet-end cylinders) have to be scraped or buffed before they become too rough. This is done on drying cylinders by using a short length of sharp, heavy deckle-blade or some other appropriate scraping device on the end of a pole which is slowly pushed across the cylinders as they are crawled round; where there is room in the cylinder pockets this procedure is speeded up by fixing two or three blades together in such a way that both an upper and lower dryer can be scraped simultaneously. On M.G. cylinders special buffing wheels are used (see **5B**.8). The insides of drying cylinders should also be inspected more frequently than is generally the case. Not a great deal can be done to remove uneven deposits of rust and scale, at least during normal scheduled shuts, and this is one potential advantage of using filming amines; but siphon tips (including the simple open-ended pipe) are a frequent source of waterlogging due to rusting, erosion, and damage, and whenever practicable one or two cylinders should be opened up on a rota each shut period for general examination and to check the clearance between siphon and cylinder.

Regular inspection and a record of the life, pattern of wear, and condition when removed of all doctors is most important, and this applies especially to M.G. and calender doctors. These are preferably placed on a preventive maintenance system to avoid neglect. Alterations to operating load and position or angle should also be noted; oscillating gear and the

loading mechanism need occasional examination. Sprays used for damping purposes require frequent attention for signs of clogging or wear in the nozzles and periodically should be tested off the machine for flow rate in different regions along their length. Rolls in which cold water is circulated, the drum reel-up, sweat roll, calender rolls, etc., need cleaning at intervals with an appropriate chemical to remove scale and rust. Hoods, H.V. in particular, hot-air nozzles, drying and other ventilation equipment all require thorough cleaning from time to time to remove accumulations of dirt and dust which block orifices and could become a fire hazard or contaminate the sheet.

Maintaining the camber on breaker stack rolls, smoothing press, M.G. pressure roll, etc. can be treated as a similar problem to press rolls. Calender roll camber maintenance is discussed in 5C.4 but it is worth noting here that any rolls in the stack not in use when the machine is running should always be greased to prevent rusting and hung separately to avoid the appearance of flat spots.

5C.2 4 Long-term records

Checking the drying section from time to time for the purpose of collecting long-term records of performance is all too rarely done in paper mills. One reason for this is undoubtedly the difficulty of obtaining sensible data, especially when different makings are frequent, and the general feeling that what measurements are made are likely to be neither accurate nor necessarily representative of the typical state of affairs. Nevertheless this is the section of the machine which is generally the costliest to run and potential savings in power and steam consumption are high enough to warrant some examination of the system at regular intervals. This is directed broadly towards two distinct ends. One is to keep a check on the drying rate and steam utilization efficiency to detect any gradual deterioration and provide data with which to compare performance should any alteration be made (e.g. type of felt used, operating conditions of felt dryers or hot-air equipment, etc.); this should embrace the ventilation system and can be as comprehensive as desired, though strictly speaking it is necessary to undertake separate checks for each of the major grades of paper produced and this increases appreciably the work involved. The other purpose of dryer tests is to ensure that the drying cylinders and flash system are retaining their general effectiveness and providing the desired pattern and uniformity of cylinder temperature through the whole section.

Consider first the question of drying rate. To determine this it is only necessary to extract samples at several places across the web both entering and leaving the drying section (for convenience this is done at the same time as testing the wire and presses, but particularly it is preferable to avoid times when wet felts are nearing the end of their life otherwise the drying efficiency can appear higher than it really is); from moisture determinations on these samples the lbs. water evaporated per lb. paper produced is calculated (using the formula quoted in 5A.2 4). The production rate multiplied by this figure then gives the appropriate drying rate. As an

alternative to breaking the sheet for samples after the last drying cylinder, it is usually considered adequate to sample off the machine roll and assume the moisture content is the same; if a sweat roll or spray damper is used, then it is necessary to revert to sampling the web leaving the dryers and also allow for the added moisture before using the production rate figure as this will be based on weight at the reel-up. The drying rate is dependent closely on steam pressure and also on the moisture content of the web entering and leaving the dryers. To interpret the data it is therefore necessary to keep note of these figures also.

This simple dryer test provides useful information but in practice the actual rate of drying on any particular machine is really important only if operating steam pressure is close to the maximum available making it very desirable that a close watch is kept on this aspect of dryer performance. A more interesting figure is the steam utilization efficiency, for which the total steam usage must also be known. Efficiency is then obtained from dividing steam used by the water evaporated in the same period; the theoretical minimum is 1·12 but normal values vary from 1·6 to over 2·0 depending partly on the grade of paper being dried. This figure is relatively independent of machine conditions, i.e. speed and moisture content of the web, and provided test data is compared for the same grade of paper it gives a more useful indication of any trends in efficiency of the drying section as a whole.

During any test of this nature other available measurements will be included relating to general running conditions in the dryers: these include steam pressures in the flash system, felt dryers, and so on; measurements of air condition in the ventilation system; load on M.G. pressure roll, breaker stacks, etc.; power consumption in the different sections; draws, sheet and felt tensions. Ideally a complete heat balance should be derived showing, possibly in the form of a Sankey diagram though this does not lend itself to comparative purposes, the heat flow in the machine house as a whole; this would cover all heat supplied in the machine house (including general heating of incoming air, of back-water and other ancilliary points), heat leaving the machine house in the condensate and air exhaust, heat usefully employed in evaporating water, together with re-circulation of heat in exchangers. A balance agreement within 10 per cent. can be considered good (especially when a machine is not hooded) because accurate sampling of air ducts and other places is difficult, especially to measure humidity (see ref. 17); it is not practicable anyway to take account of all heat sources (e.g. from motors and friction) or heat losses (e.g. evaporation from open surfaces and general building losses). Certain values such as the temperature of the condensate water vary little and have only a small effect on the heat calculation; these may safely be taken as standard. Other values such as air flows are best calculated using fan performance curves. Humidity is most accurately determined with conventional wet and dry bulb thermometers, though hair hygrometers and dew point measuring devices are most convenient.

Several key figures can be derived which aid interpretation of such comprehensive data. In particular it is useful to know the proportion of the

heat supplied which is usefully used (another measure of utilization efficiency), the overall heat losses and their relation to ambient temperatures, the weight of air used in comparison with moisture evaporated (a measure of ventilation efficiency and dependent on incoming humidity which governs the amount of moisture it is possible for the air to pick up), and the relation between power and steam usage with particular emphasis on hot-air supply units. In addition periodic tests of this thoroughness help to show up deficiencies in such things as fan operation, heat-exchange equipment, hot-air nozzles, etc. A good illustration of the determination and derivation of this sort of information together with a suitable means of setting out the various figures has been reported by Chalmers (8), to which reference may be made for further details. Other illustrations and some case studies appear in an article by Mardon *et al.* (125).

It is obvious that the large number of different positions at which it is necessary to check air condition for velocity, temperature and humidity, determine flows of steam, and so forth means that a substantial amount of work is entailed. Making provision for such tests by fixing suitable tapping points in air ducts and installing separate flow meters, pressure gauges, ammeters, etc. at key points can be quite an expensive business. Possibly the best solution in the case of a mill venturing into this field for the first time is to consult a heating and ventilation expert who could advise on what measurements are needed and where they should be taken. As a preliminary to this it will be necessary to survey the whole system, including probably the boiler plant and power generation units, and this may well produce valuable suggestions leading to economies in running cost. In connection with this, in this country the National Industrial Fuel Efficiency Service is an obvious body to turn to (66).

The other aspect of the dryers requiring periodic checks relates primarily to the effect of drying on the paper. To this end it is most important to check the rate of heating up of the sheet and the subsequent drying gradient. The usual method adopted is to determine the surface temperature of each cylinder using a pyrometer attached to a suitable bar. Although none of the various makes of pyrometer available can be relied on to give very accurate measurements of absolute temperature, for comparative purposes in any one test most types are satisfactory provided cylinders are not coated with scale (this changes the closeness of contact and emissivity of the metal surface, both of which affect the temperature sensitive element); to avoid the influence of frictional heat (and reduce the degree of discomfort involved) response time of the instrument should be rapid. The average temperatures of top and bottom cylinders generally differ, but the difference between adjacent top or adjacent bottom cylinders need not exceed about 5 deg. F. The gradient of temperature rise at the beginning of the dryers (and in some cases the fall at the end) can be usefully checked by this means, but perhaps the greatest benefit derives from pinpointing waterlogged cylinders.

An alternative measurement is to time the condensate flow from each cylinder but for this it is necessary to install a T-branch on the condensate line with suitable cocks to divert the flow either into a steam trap or, when

suitable, direct to atmosphere; a bucket and stopwatch suffices to check the flow rate. The trouble with this method is that under the usual conditions of measurement the pressure on the condensate line from the cylinder is altered when the flow is diverted: it may be raised if a steam trap is used or lowered if the flow is allowed to discharge to atmosphere. This could alter the volume of condensate in the cylinder and affect the conditions inside sufficiently to change the condensation rate. It is however likely that any change will be relatively small as the main factor governing condensation rate is heat demand from the paper; provided the temperature of the inner surface of the cylinder is relatively unaltered, i.e. the thermal insulation of condensate in the cylinder is unaffected, then the heat transfer rate and hence the condensation rate should be unaltered too. But as a precaution when using this method condensate flow from any cylinder must be allowed ample time to settle down before measurement is made. In any case the flow rate between cylinders working at substantially different pressures (e.g. at a change in flash section) must be compared with caution. It may be noted that there is a relatively simple means of avoiding this particular difficulty and this is by making provision for installing a pressure gauge and a valve in each condensate line; with the flow diverted the valve is then used to adjust the pressure before measurement to make it the same as during normal operation.

Other measurements desirable for long-term comparisons of the effect of drying on the paper are various checks of air conditions within the pockets and by the side of the cylinders. Temperature and humidity require measurement with standard instruments at a number of defined positions, and air velocity can usefully be measured with a velometer type instrument. The web itself can be sampled at various points in the drying section and tested for moisture content and temperature; for this purpose it is best to use two cutters on the wire about 9 to 12 inches apart in such a position as to allow a piece of the web as far from the edge as possible to be grabbed. The accuracy of this type of test is not great due to the continually changing condition of the web in each open draw (in particular temperature falls rapidly as evaporation occurs in the first few inches after leaving the cylinder surface), but for rough comparative purposes of the drying rate at various positions in the section it is quite satisfactory. The width of the sheet entering and leaving the dryers provides a measure of the cross-machine shrinkage rate.

To complete information for long-term records, conditions in the calenders with regard to load, number of nips used, steam or water flow and pressure, etc., pressure of winding at the reel-up, water flow to dampers, and of course quality tests on the paper itself are all required. Cross-web temperature checks for cylinders and calenders may be considered a worthwhile addition in some circumstances but would not normally form part of the measurements taken for the purpose under consideration. If differential pressure tappings are available on the steam and condensate lines to each cylinder these pressures can also be checked, but this information is more useful for specific trouble-shooting than for long-term records.

5C.3 CONTROL OF MOISTURE CONTENT

It is the dryerman's duty to regulate moisture content of the sheet at the reel-up, and on most machines this is likely to be the most important of his tasks and the one which requires most skill. This applies especially to the need to attain uniform moisture content across the width of the web, a problem which is one of the most pressing in need of solution. Reasons for the importance of moisture control and the means available for achieving uniformity in both machine and cross-direction is the subject of this section.

5C.3 1 Moisture content and its relation to substance

If asked which is the most important property of a paper that must be kept in specification, most production personnel will undoubtedly agree on substance. And certainly every grade of paper must be matched as closely as possible in substance if it is to have some semblance of continuity from one making to the next. But once the machine has been adjusted to give a substance approximating to that required, it is debatable that moisture content then becomes the more vital variable to keep under close supervision and control.

There are several reasons for this, the most important being that satisfactory uniformity of substance in any case cannot be achieved without reasonable moisture control. This is because moisture in the paper is an integral part of the substance, and if the moisture content can vary appreciably there is no means of telling whether a change in substance should be corrected by an alteration to the fresh stuff valve, or the steam flow valve, or both. To make this clear, suppose that moisture content does in fact vary on a machine and no means is available for its measurement; then an observed substance increase (above that required) of, say, 3 per cent. at the end of a particular machine roll could be caused equally well by a 3 per cent. increase in fibre entering the machine system as fresh stuff, or by a 3 per cent. increase in the moisture content, and is more likely to be due to a combination of both. There is no means of distinguishing the effect of dry fibre or moisture solely by weighing the paper.

Even when the moisture content is known precisely (a difficult enough matter, as will be discussed shortly), the remedy for the 3 per cent. increase in substance will not be immediately obvious. Suppose for the sake of argument that it is found by end-of-roll testing that moisture has increased by 1 per cent. at the same time that the substance has shown the increase of 3 per cent. The normal reaction to correct the situation would be for the machineman to alter the stuff valve to reduce substance by 3 per cent., while the dryerman alters the steam valve to reduce moisture by 1 per cent., each thereby correcting the observed errors in the property under his supervision. But the result of this combined effort may well be that at the next roll testing reveals substance to have decreased not by 3 per cent. but by as much as $5\frac{1}{2}$ per cent., thereby making it $2\frac{1}{2}$ per cent. light instead of correct weight, while moisture content has decreased not 1 per cent. back to its former level but by no less than $2\frac{1}{2}$ per cent.! Both machineman and dryerman would then take drastic action, this time to increase substance

and moisture, and the way is open to a session of wild hunting about the required values that is a common feature of process control charts.

At first sight this example of the changes that might occur in such a situation seems incredible, but a little careful consideration of what happens when substance is deliberately altered makes the reason clearer. Results on the first roll (substance up 3 per cent., moisture content up 1 per cent.) could well be due entirely to an increase of the order of 2 per cent. in the flow of fresh fibre to the machine, i.e. in the dry weight of the sheet; this is because a 2 per cent. increase in weight of fibre to be dried reduces the overall rate of drying per unit area of web, and this could easily result in the measured increase of 1 per cent. in moisture content. A 1 per cent. moisture increase added to the 2 per cent. increase in dry weight produces the observed 3 per cent. increase in substance. The remedy would therefore be simply to alter the fresh stuff valve appropriately, leaving the steam valve untouched. If instead the fresh stuff valve is altered to produce a 3 per cent. drop in substance, this could, if the change were in fact equivalent to decreasing the dry weight by 3 per cent., lead to a decrease of about $4\frac{1}{2}$ per cent. in substance due to the additional reduction of $1\frac{1}{2}$ per cent. in moisture content. Alteration of the steam valve by the dryerman to give a further 1 per cent. drop in moisture content in an attempt to correct the original condition leads to the overall decrease of $5\frac{1}{2}$ per cent. in substance and $2\frac{1}{2}$ per cent. in moisture content.

This example must be subject to some qualification as it depends on the assumption that a 1 per cent. change in dry weight of fibre will cause an additional change of $\frac{1}{2}$ per cent. in the moisture content—a purely hypothetical figure. But undoubtedly some drop in moisture content must occur when a lower quantity of fibre requires drying, just as it would were the speed to be decreased slightly; the precise degree of change will depend on the drying characteristics of the machine, behaviour of steam flow in response to alteration in demand, and so forth, and also on the level of the moisture content (higher values being more sensitive to changing conditions than lower ones). But the example does serve to illustrate the sort of dependence of substance on moisture which can be expected in practice.

Two points of importance emerge. Firstly, alterations of substance (in the sense of changing fresh stuff valve position) and of moisture need to be carefully correlated. The machineman and dryerman cannot go their own ways independently, the one checking substance, the other moisture, as their actions mutually affect each other. If the machineman finds cause to alter the fresh stuff valve, the dryerman should be warned of an impending change in moisture content. If the dryerman alters the steam valve position, this may affect the substance to a degree which causes the machineman unnecessarily to consider changing the fresh stuff valve position. It is not possible to lay down any rigid procedure as this depends on the methods available for measurement of both substance and moisture. But probably the simplest aim is to keep moisture content as steady as possible by one of the methods discussed below, then the machineman can more easily take account of probable variations in moisture content before moving the fresh stuff valve, making an alteration which allows for the fact that moisture

will also change and have its own effect on the apparent substance (this he in fact learns to do in practice by observing how a given movement of the valve affects substance). For efficient regulation of both properties it is really necessary to control not substance but dry fibre weight, a subject that has already been dealt with in 1C.3.

5C.3 2 Other reasons for controlling moisture content

There are several other reasons why it is important that moisture content at the reel-up is controlled (using the general sense of the word). Firstly, any sample extracted from the machine roll begins to pick up moisture at a rate dependent on the initial moisture content and on the ambient air conditions (the latter affect the equilibrium moisture content the paper would eventually attain). Hence when substance is measured on samples torn off at the reel-up in the usual way, the result is affected by the gain in moisture content up to the time the weighing is completed. The complication this adds to the machineman's job of keeping the making substance consistent and close to the specified value has been discussed more fully in 1C.3. The less variable the moisture content at the reel-up, the easier it is to overcome this particular difficulty and make an allowance for the difference between substance as measured and as required.

Another reason for the importance of moisture control is the dependence of calendering on this property. Any change in moisture in the paper at the calenders will create variation in the surface and bulking characteristics of the sheet. The work of Brecht and Heyn (33) discussed in 5A.4 3 indicates the existence of an optimum moisture content for maximum smoothness, but this is at about 15 per cent. moisture and so in practice increasing moisture content at the reel-up can be expected to yield an overall increase in smoothness and a decrease in bulk. This in turn affects other properties of the sheet after calendering. With an M.G. machine, the moisture content at the M.G. cylinder has a critical effect on the glazed finish of the sheet.

A final reason, probably the most valuable of all, is that generally speaking it is almost always advantageous to obtain as high a moisture content as possible in the sheet at the reel-up. To achieve this some form of control becomes essential because the higher the moisture the more variable it is liable to be. Attempting to obtain high moisture in the machine roll without adequate regulation only leads to substantial wastage either from blackening in the calenders or from creasing at the winder due to uncontrollable differences in reeling hardness across the web.

The advantages of a high moisture content are worth examining for a moment because they present in many ways the crux of the need for control of this property and the potential advantages to be gained.

A high natural moisture content at the reel-up saves running costs because less steam is used for drying. It also diminishes the likelihood of static in the sheet and improves fold, stretch, tear and flexibility properties, which are actually also those most affected by fluctuations in moisture content resulting from changing ambient air conditions. For paper sold in reel form high moisture content represents a considerable saving because water is cheaper than the furnish. When sold in sheet form the same applies

517

but to a lesser extent (because it is more likely that moisture is picked up during cutting, sorting and counting). Usually, however, reels are conditioned to bring up the moisture content closer to its equilibrium value in air. This is an expensive separate process, though with fine papers it often becomes essential because it reduces the cockling and curl that otherwise occurs if the sheet is allowed to pick up moisture naturally. Although in theory conditioning should ensure that the paper is sold with adequate water content, in fact it is more than likely that making substance on the machine will be higher than it need be because the weight increase as moisture is picked up will be underestimated—hence the weight of a ream (and the furnish gone into it) will also be greater than necessary. Finally, the higher the moisture content initially, the less is picked up before equilibrium is reached; as pick-up of moisture produces deterioration in smoothness and other qualities this is usually a further advantage to producing a high natural moisture content at the reel-up.

5C.3 3 Measurement of moisture; general comments

To be able to control moisture content adequately implies that it must first be measured with reasonable accuracy. It is precisely here that the biggest difficulty arises. None of the laboratory methods for determining moisture content by oven-drying, distillation, vacuum desiccation, hot-plate and infra-red drying, titration, and so forth are suitable for process control purposes, mainly due to the time involved in obtaining individual readings. For this reason a variety of portable instruments for measuring moisture content have been marketed and these operate in several ways depending principally on detecting the variation in electrical resistance or dielectric constant (capacitance) of paper which takes place as the moisture content alters (see next section).

There are two disadvantages to the use of such instruments for moisture measurement. In the first place, even with the instrument by the side of the machine it is extremely difficult to sample and test sufficiently quickly to prevent a significant pick-up of moisture. Immediately exposure of the test piece takes place, and this applies particularly in the damp atmosphere of the machine house, the moisture content increases at a rapid rate: when paper is made very dry on the machine, say in the 2 to 3 per cent. region, it can in fact prove almost impossible without elaborate precautions to obtain a reading below 5 per cent. If the sample is drawn from well below the surface of the machine roll, then plunged into a plastic bag, weighed, and moisture content determined by oven-drying, a very accurate result can be expected. But if the sample is drawn from the same position and one of the usual testing instruments is used, then the reading is invariably higher due to the impossibility of avoiding some moisture pick-up before the test result is obtained. The only way this can be minimised is by cutting a layer of sheets off the machine roll and keeping the instrument well inside the layer while measuring selected pieces.

The other disadvantages inherent in the use of an instrument is that it has to be calibrated, and the calibration is rarely the same for different types of paper. On machines making few grades this can present little

difficulty, but where a variety of loadings, furnishes and substances are used it becomes an irksome task to check up on each grade. Frequently also the relationship between instrument reading and moisture content is not linear, so the task of calibration is further complicated. Under these conditions it becomes inevitable that less reliance is placed on the actual reading obtained on any sample, provided it is known to bear some relationship to the absolute value, and more emphasis is given to the variation from one sample to the next; in other words the instrument becomes used primarily as a deviation meter.

These drawbacks to the use of off-machine moisture-measuring instruments have led to the demand for instruments for measuring directly on the paper machine web; these carry the advantage of making available a continuous reading of moisture content, a facility having obvious value. For this reason much effort has been made by instrument manufacturers to develop suitable devices for on-machine measurement.

5C.3 4 Continuous measurement of moisture content

Few devices for the paper machine have stimulated such a wide variety of ideas as those directed to improving moisture control. It is not proposed here to enter into a detailed survey of the different methods designed or proposed (for many the information available is little better than sales literature); this has been done already by many authors, notably Hurm (62). What follows represents just a very brief summary of the salient features of each method.

Continuous moisture-measuring devices can be divided broadly into two groups: those attempting to measure some aspect of the machine or the paper web which is known to be dependent on moisture content, and those measuring moisture content of the web directly at a point close to the reel-up. Into the first group fall the following systems:

(a) The use of a tension roll or bar in an open draw between two cylinders near the end of the drying section; movement of the roll or bar depends on varying shrinkage in the web and this is taken as an indication of moisture.

(b) Measurement of sheet temperature with thermocouples placed at fixed positions a short distance after the web leaves a pressure-controlled dryer, the surface temperature of which is also measured for reference (Hurletron system); this method relies on the temperature drop of the web leaving a drying cylinder being related to the moisture content—the higher the moisture content, the greater the temperature drop resulting from evaporation.

(c) Measurement of the steam (or condensate) flow in a pressure-controlled pilot drying cylinder (Stamm system); this depends on the fact that the more moisture there is in the web as it comes on to the dryer, the slower the web will be to heat up and, as a consequence, the greater will be the heat demand and the steam flow into the cylinder.

(d) As an alternative to (c) the flow of steam can be controlled and variation of the inside temperature of the cylinder measured.

(e) A further alternative to (c) is to measure the surface temperature of the pressure-controlled cylinder, this being lower when there is more moisture in the web; the difficulty with this method is that continuous measurement of surface temperature by one or other of the contacting instruments commonly used for spot-checking has not to date proved satisfactory due to the effects of accumulations of fibre debris and scale on the cylinder surface and on the instrument response surface itself (though see references 6 and 34 for designs which are claimed to overcome this problem).

Each of these systems has serious inadequacies. In particular, each is dependent on substance and sheet structure (as these affect the drying characteristics) and on the machine speed and general drying conditions (ventilation and felt conditions, condensing variables, etc.); also calibration is difficult and in most cases reliance has to be placed on an empirical approach in which the measuring device is coupled to an appropriate control (normally the main steam supply valve) and a working position found which appears best to stabilize the moisture content at the reel-up. Nevertheless, any of these systems may be expected to improve the situation on a machine with hitherto uncontrolled steam admission and so can be justified as better than nothing, though whether the improvement is better than can be achieved simply by controlling the steam supply temperature as discussed in 5C.14 is open to doubt. As control systems they generally have an advantage over reel-up moisture devices in enabling earlier detection of changes, thus reducing the time-lag for correction. But they cannot produce a record which can be taken to represent moisture content at the place where it matters, the reel-up, nor (except possibly for the second system) can they be adapted for measurement of moisture across the web.

The second group, moisture-measuring instruments which are used on the web close to the reel-up, includes the following systems:

(f) Measurement of the electrical resistance or conductivity across the paper using d.c. or a.c. current and metal rollers or finger electrodes contacting the web on both sides (Brown Moist-o-graph, Aquatel, etc.); this is a well-tested system though the reading is affected to a greater or lesser degree by the thickness of the sheet, the compressibility (or, alternatively, the pressure of the electrodes on the web), temperature, and the presence of static and electrolytes in the web.

(g) Measurement of electrical resistance between electrodes on the same side of the sheet (Shirley system); this has the advantage that it is simpler to mount on the paper machine but still suffers from the same disadvantages as (f).

(h) Measurement of electrical capacity or dielectric constant usually between concentric or parallel-finger electrodes contacting one side of the paper web (Lippke, Baldwin, Foxboro, etc.); this too is a well-tried system which remains sensitive down to moisture values of the order of 2 per cent., but it suffers from non-linearity of

response to varying moisture content and is affected by substance, to a lesser extent by the furnish and certain additives, and also in some cases by the temperature of the head (but hardly at all by other factors).

(i) Similar to (h) but with two non-contacting electrodes on either side of the web (EKCO); this technique permits high moisture readings to be measured and has potential applications at the press as well as the reel-up.

(j) Measurement of air humidity close to the sheet, a property which has been found to correspond closely to the moisture content (Atrometer system); this has the advantage that direct contact with the web is not needed, but careful shielding is required as the reading is affected by web (and air) temperature and by draughts, also the hygroscopic elements are prone to dust and dirt, and require frequent cleaning.

(k) Measurement of the absorption of microwave energy at specially-selected wave-lengths (Beloit); this, too, has the advantage that the instrument need not touch the sheet, but to date relatively little is known of the performance and accuracy of this method.

(l) Measurement by absorption of ultrasonic sound waves, or by absorption or reflection of infra-red and ultra-violet radiation (G. E. Inframike and Pier); little is known of the potentials of these techniques either.

Choice between these various systems of reel-up moisture measurement is difficult. Many, especially (h), have been gradually improved over the years in respect of their mechanical construction (particularly in regard to automatic or rapid retraction out of the way at a break) and different correction factors have been built-in to remove non-linearity of response, the effect of substance, and so forth. It remains the case, unfortunately, that whatever type of instrument is used a great deal of calibration work is necessary on machines that run a variety of different grades of paper; a routine standardization procedure is also essential, though this is not usually difficult or time-consuming. In addition the detecting heads are frequently subject to damage when they are in exposed positions between the dryers and calenders or between the calenders and reel-up, and often need regular cleaning to prevent dust accumulating and affecting the reading. But with systematic attention from the instrument personnel and training of the dryermen to use and appreciate the value of the moisture reading, such instruments have an important rôle on the machine.

With a continuous measurement of moisture content available the dryerman very soon becomes aware of two important phenomena. In the first place he discovers that the variability of moisture in the machine direction is much greater when the web is reeled damper: with the same instrument response time the range of fluctuation can be as little as 0·1 per cent. or 0·2 per cent. if moisture content is in the 5 per cent. region, rising to 0·5 per cent. in the 7 per cent. moisture region, and with fluctuations of up to 2 per cent. or more in the 9 per cent. region. Stability is greater when

steam pressure is controlled, and is closely dependent on the amplitude of short-term substance fluctuations, but on all machines it is found that moisture content at the reel-up is relatively much more unstable if the web is run damper. This is one of the main difficulties involved in achieving as high a moisture content as possible.

The other point which becomes immediately apparent with a continuously-measuring moisture meter is that a difference in response is likely according to whether the main steam pressure in the cylinders is increased or decreased. If steam pressure is increased, under typical conditions, the moisture content can take as long as 10 minutes to stabilize at the lower level corresponding to the new steam valve setting; but if the steam pressure is then reduced back, the response is generally much more rapid and the moisture content stabilizes at its former value in a matter of 2 to 3 minutes.

One of the more important advantages of having a continuous moisture measurement is that it becomes much simpler to achieve the desired moisture level quickly and accurately after a wet-end break. When cylinders are run for even a relatively short time without the web passing over them, they rapidly heat up and the felts dry out; it is therefore normal practice with a wet-end break of any duration to prevent excessive heating up of both cylinders and felts either by reducing the steam pressure to the main section and the felt dryers (while maintaining adequate pressure differential to avoid waterlogging) or by switching over to separate steam valves. When the web is fed through the drying section again the original steam valve positions must be re-instated at an appropriate time. Ideally, this should be chosen at the point when the time-lag in response to the controller action is best balanced against depletion of the reserve of heat in the cylinders and the re-gaining of moisture by the felts; this will ensure that the web at the reel-up becomes neither too dry (when it tends to break) nor too damp (when it sticks to the calenders). Determination of the best means of dealing with a wet-end break and then feeding-up smoothly, i.e. finding the steam pressure to which a decrease is desirable when the break has occurred and the most suitable moment during feeding up when reversion to the former pressure is arranged, is much simpler when a continuous moisture meter is available. In some cases it has been found beneficial to increase the steam pressure temporarily to a value greater than the normal running condition, thereby giving an initial 'kick' to attain that condition quickly. Systematic application of a routine procedure for altering steam conditions at the beginning of a break and when feeding-up again eliminates a large source of downtime. As an aid to determining these conditions knowledge of the behaviour of the surface temperature of selected cylinders as the web is fed through would be of assistance; unfortunately though this is not the best of times to be wielding pyrometers in the dryers. A simpler indication which helps to determine the feed-up procedure that achieves drying equilibrium quickly is the behaviour of the felt stretch gear; Roger and Webster (20) showed that moisture content of dry felts could take 15 minutes or more to approach equilibrium after a break, and as the moisture content is closely related to the running length of the felt, observation of the stretch gear assists in setting the steam

pressure at a break and gives an indication if much change is still taking place in drying conditions after the web is fed through again.

5C.3 5 Automatic control of moisture content

From measurement of moisture content to automatic control is a logical step, and it would be quite possible to link up any of the measuring devices listed above with the main steam supply valve. In this way the valve opening could be regulated to keep the moisture content (or, to be more precise, the instrument reading) steady at some desired value. In practice it is rare for such a direct form of control to be installed and it is generally agreed that a better and more flexible arrangement results from using the moisture meter reading to regulate the set-point of a separate steam temperature or pressure controller in what is termed a cascade control system.

The main advantage of having such an arrangement is that the response characteristics of the steam controller can be chosen to deal best with overall fluctuations in supply and demand of the dryers, while the moisture meter response characteristics are chosen to keep movements of the steam controller set-point damped sufficiently to take account of the long time-lag and slow response of this part of the system. Such a combination gives an overall better performance than a direct control set-up. A further advantage is that failure of the moisture meter, or the need to shut off the meter signal temporarily to allow a cross-web traverse or clean the detector head, does not mean that control of the main steam valve must become manual; instead, the moisture meter output can simply be locked and the steam controller continues to function and maintain drying pressure according to the original set-point. It is also easier to prevent a sharp change to the steam control valve ('bumpless transfer') either when the moisture meter is switched back into use or in the event of a change being necessary to the moisture set-point.

With a cascade system of this type, in addition to recording the moisture reading it is absolutely essential that a record is kept of the main valve opening (usually on the same chart as the steam temperature or pressure). It is relatively simple to arrange for a break-detector system to move the moisture meter out of the way and lock the signal when the sheet breaks, while at the same time (in the case of a wet-end break) the steam controller set-point can be moved to a lower level to suit conditions with no paper in the dryers, as discussed in the previous section. There would then be manual or automatic reset to the former working position of the steam controller as the sheet is fed through, with the moisture meter signal reintroduced when the web has again reached the reel-up.

Those moisture-measuring systems which effectively average the whole web appear at first sight to be most suited to this form of moisture control. But in fact, it is preferable to have a detector head which measures only a relatively narrow portion of the web in order that the position of the head can be chosen to effect control over the dampest place where the sheet is liable to cause the most trouble if moisture content becomes excessively high. Also, most types of detector head suit a traversing arrangement and

thus allow some form of measurement of the cross-web variation (see following sections).

Although ultimate control is normally thought of as applying to the main steam supply valve, this regulates the whole drying section and the large thermal capacity then means that response can at best only be slow. It is preferable instead, whenever possible, to control the steam supply to a small bank of four or six cylinders at the end of the drying section, thereby giving a much quicker and more sensitive response. The danger from this practice is that the maximum steam pressure available for the control section may be frequently reached, or alternatively the steam supply may be shut off to such a degree that the cylinders begin to sweat; for this reason, some precaution is advisable with this form of control to ensure that the main steam valve or the main pressure controller is altered should the valve opening on the separate bank exceed pre-set upper and lower limits. An alternative system which is claimed to improve response is to alter the temperature or velocity of air in a high-velocity-air hood; there is some difference of opinion about which hood operating characteristic is the more suitable to alter, and the choice must depend on the relative ease with which the control can be arranged and its effect on the overall efficiency of the hood. Successful moisture control by changing the air flow to hot-air blowing felt rolls has also been reported (124).

5C.3 6 Unevenness of moisture content across the web

Of all the properties of paper, the one which is invariably the least uniform across the width of the machine is moisture. This has many important consequences. In the first place the more uneven the moisture, the lower will be the average moisture for the whole web because the dampest position must always be kept below the moisture content at which blackening occurs; further, greater variation from one moment to the next is found at higher moisture values so the dampest position has in practice to be run at a moisture which is well below the blackening point.

It becomes more difficult to build a uniform machine roll when moisture is uneven because damp places tend to be thinner and slackly wound (a direct consequence of the greater calendering effect on moister paper); differences in reeling-hardness across the roll become accentuated on the supercalender or winder, where the regions of uneven moisture are likely to run into creases. To offset this effect the dryerman has recourse to the calender air blowers, but frequently substance in the offending damp positions has also to be reduced to dry the region down sufficiently; this is all right provided high substance in the relevant positions across the web were the original cause of the moisture being high, but if the substance were correct in the first place then the slack area is removed only at the expense of introducing some other lack of uniformity. The problems arising from these difficulties are dealt with in more detail in 5C.4.

Most properties, in particular fold, stretch and tear, are sensitive to moisture content, so that variation of moisture across the web will in turn introduce variations in these other properties. Also, as regions with initially higher moisture content pick up less moisture before reaching

equilibrium in ambient air conditions, this will introduce differences in the behaviour of different parts of the sheet and be a source of, amongst other things, curl and cockling. Curl can in addition be caused directly as a result of the differential drying rate associated with damp regions in the web. Finally, the effect of calenders is very sensitive to moisture content so that areas passing damper through the calenders will, on average, be smoother.

Cross-web moisture differences thus require very close attention. They generally arise from two distinct sources. Firstly, there are differences which must be regarded as more or less permanent and a direct character-istic of the machine operation. These include general ventilation deficien-cies, poor cambers on the press rolls, inadequate hot-air supply to cylinder pockets, and so on; their commonest manifestation is in the form of dry edges, and numerous ways have been thought of and tried to overcome this defect. It is not proposed to discuss these in detail as mention was made of the main approaches that have been attempted when discussing require-ments of the condensate removal and ventilation systems. The greatest difficulty in adapting the overall moisture profile is the labour involved in achieving the right degree of compensation which is at the same time suitable for all machine operating conditions; also a ready means of determining moisture across the web is essential to assess the effect of the changes made.

Even then it is by no means clear what alterations are likely to have the effect desired. As an example of this, Harrison (60) mentions that in order to try and improve the moisture profile on one machine amongst other things the felt air-supply system was altered and enlarged, the Grewin system was altered, and the front side of the dryer framing was closed in to correspond with the enclosed gears at the back of the machine—each of these changes brought little, if any, improvement in the general moisture profile and it is disheartening to observe how erratic the reel-up moisture remained even when both the substance and moisture entering the cylinders were relatively uniform.

The other sources of cross-web moisture unevenness are those which gradually change in complexion over a matter of hours or days, and originate from such things as wet or dry felt deficiencies, temporary substance unevenness, scaling up of the inner or outer surfaces of drying cylinders, hot-air ventilation nozzles which have become blocked or knocked out of position, and so forth. These cannot be allowed for by any permanent alterations to the machine and are often very difficult to trace and remedy. As there is no means available to correct the moisture content in the (often narrow) regions of the web affected, all that can be done is to play with the substance and calender air blowers. It is in this sphere particularly that moisture measurement tied with some means of correction at different positions across the web has much to contribute.

5C.3 7 Measuring moisture content across the web

Moisture content across the web at the reel-up can be measured by careful sampling and oven-drying, but for regular use it becomes essential to use

one of the instruments described above. The main purpose is specifically to compare moisture content at different positions, so absolute accuracy of reading is not so important provided consistent results can be obtained.

Any of the portable instruments can be used to obtain cross-web measurements on a strip off the machine roll provided ample precautions are taken to avoid air getting to the sheet before the reading is obtained. This makes it necessary to tear off a minimum of a dozen or so thicknesses of paper, select specimens for testing from the middle of this pile, then so far as possible thrust the whole instrument within the pile of paper to obtain the reading. To avoid systematic error, such as may occur if the series of readings are always obtained in the same sequence from one side to the other, it is preferable to randomize the order of testing positions. The spacing at which tests are performed is generally about 6 in., though this may be widened if the procedure becomes too time-consuming.

A different approach, which is not limited to end-of-roll testing, is to use an instrument adapted so that it can be held against the machine roll by hand. Provided reasonable consistency of reading is achieved and the hand-held instrument is kept relatively free from operator error, such a device could prove more flexible and much quicker to use than the normal form of portable instrument. The main disadvantage is that it does not lend itself to providing a permanent record of results obtained, and there would be less likelihood of the dryerman being able to apply systematic correction to moisture differences.

Adaptation of one or other of the various types of on-machine instruments to traverse the web and give a continuous record of moisture at all positions has obvious advantages, though unfortunately this is apt to become rather expensive and involve cumbersome equipment stretching across the machine. The general principles of using different arrangements for traversing, in particular choice between different methods of presenting the readings and co-ordination with the measurement of machine-direction variation, are very similar to those described for traversing beta-ray gauges (see 1C.34); in fact to a large degree the full value of a traversing moisture meter is only realized if linked to a traversing beta-ray gauge (see for example reference (56)). The system used must be chosen to suit the behaviour of the paper machine in question, the relative variability of moisture in machine and cross directions deciding, for example, whether several measuring-heads are placed in fixed positions across the machine or a single head is used, this being kept for most of the time in one position to give machine-direction measurement but also traversing the web at fixed intervals. When using a traversing head, the most usual and flexible method, the instrument response time requires careful setting in relation to the traversing speed (which for practical purposes is usually from 1 to 2 minutes) in order to produce a profile which shows up variations that are possible to identify and correct; too damped a response does not show up moisture streaks that are present, while too rapid a response produces such a wildly fluctuating trace that interpretation becomes difficult.

5C.3 8 Control of moisture content across the web

Installing any cross-web moisture-measuring system, however comprehensive and accurate, is unfortunately only half the battle, for the dryerman has few facilities to make any form of correction other than those afforded by altering press loading or the substance profile. Indications of damp streaks will be useful for pinpointing the position of trouble, and encourage earlier investigation than is likely if the dryerman has to rely on feeling the roll. But to obtain full benefit from an on-machine cross-web moisture-measuring system it is necessary to provide some means of correcting the moisture profile; in some cases this could even be made automatic, though whether this is worthwhile is open to argument, and must depend to some extent on how rapidly the cross-web moisture varies.

Many methods of moisture correction have been described, but as yet none are really outstanding. Sprays, fixed in the early part of the dryers at close (6 in.) intervals across the machine and giving an adjustable flow of hot water on to the web, form the basis of one method for which some success has been claimed (59, 112). It was found advantageous in this case to make the controlling system automatic and a special unit was devised to arrange successive alteration of a series of needle valves each of which regulated flow to a single spray; to keep the total quantity of water added at the sprays to a minimum it was necessary to ensure that at least at one position the spray valve was left fully closed. An obvious criticism of this system is that it is a retrograde step to add water to the web at any stage of the dryers, but extra running costs involved in this must be compared to the advantages gained by the control (it is quite possible anyway that despite the water addition, less steam is used in the dryers because of the higher average moisture which becomes possible). Also the capital cost of the equipment is relatively low. Adjustable sprays on a dry felt rather than the web provide an alternative method that has been suggested, but this does not appear in practice to prove very effective. Steam jets are a further possibility.

Another method of controlling cross-web moisture, which could also be made automatic though this is not usual, is to use a sectionalized H.V. hood; this hood is divided into 12 in. to 15 in. compartments across the machine and the air flow to each compartment can be individually regulated, normally by means of simple dampers. An installation using this system has been described by Harrison (60) (this involved separate measuring-heads opposite each compartment—a rather expensive business, one would think) and also by Attwood and Hitchen (110). Use is also made of high-velocity air at high humidity in an on-machine conditioning device (121) which, it is claimed, not only adds moisture to the web but also makes the profile more even. This, however, must be regarded not so much as a control device as a means of improving moisture profile. Finally hot-air blowing felt rolls in association with plastic fabric dry felts have been used successfully for improving moisture profile (124, 130) though it is doubtful if true control would be possible.

Other methods of moisture correction have been suggested, including the use of banks of infra-red heaters or micro-wave dryers the output of

which can be varied across the machine. Another idea has been to apply differential vacuum across the wire, but any effect this had would almost certainly be all but eliminated in the presses. As yet, however, nothing has appeared which offers a relatively cheap and simple means of altering the moisture profile without incurring a very heavy capital cost. One basic difficulty is to obtain a technique of correction which is sufficiently adaptable to be able to overcome the quite narrow streaks of dampness that are the main source of trouble on most machines; sectionalized hoods, for example, cannot satisfactorily cope with really narrow streaks, especially when these are severe, and any large alteration of heating capacity necessary in one compartment has the effect of changing the capacity of adjacent compartments. The correction should also have a relatively quick response, i.e. thermal capacity must be reasonably small, though it is not essential for correction to be made at the end rather than the beginning of the dryers simply in order to reduce time-lag; probably the best place is before serious differential contraction effects are introduced, i.e. not later than two-thirds of the way down the drying section.

With any method permitting adjustment of moisture content across the machine, it is imperative that a clear limit is imposed on the degree of correction possible in any one position. The control allowed must, in other words, be regarded as a final trimming device which corrects faults and unevennesses that it is impossible to remove in any other way. The substance profile must be set first, then any general lack of uniformity in moisture profile due to unsuitable press cambers, dry edges, and so forth must be eliminated so far as possible by other means, and only then should the moisture correction be used. If this is not done there is a serious danger that the dryerman will come to depend on any moisture correction system to remove all the faults that appear, instead of seeking first to eliminate these at source, and this could well result in the paper lacking uniformity across the machine even with a good moisture at the reel-up due to the differential pressing and drying conditions experienced by different portions of the web. For the same reason, it is essential not only to provide a record of the moisture profile, but also one which indicates the degree of correction applied at each position with clearly marked limits showing the maximum desirable—only with this facility will there be a deterrent to placing too much reliance on any available control.

5C.4 CONTROL OF THICKNESS

The thickness or caliper of paper at the reel-up is controlled by operation of the calenders, with, in some cases, assistance from a breaker stack. On thicker grades of paper and paperboard the thickness is important in itself, but on all grades, especially those required for printing, the close relationship between surface smoothness and thickness means that control of the latter is no less essential. It is the dryerman's duty to supervise this control.

5C.4 1 General comments on thickness control

Measurement and control of thickness in the machine direction presents relatively few problems. The standard test method allows the average value

of a sample drawn from the top of a machine roll to be rapidly obtained. Even though some increase in thickness will occur after extraction from the reel, due partly to moisture pick-up and partly to relaxation of compression forces (see Fig. 5.13), this generally seems to be relatively slight and within the accuracies of working can effectively be ignored. Changes in thickness on the machine are of a long-term nature so that adequate control should normally be achieved simply by using an end-of-reel process control system and altering calender loading as necessary.

Control of thickness in the machine direction thus presents relatively little difficulty. Unfortunately this cannot be said for control across the width of the web. This is particularly important at the reel-up because uniformity of thickness closely affects the evenness of reeling-hardness or tightness of the roll; although the machine roll may appear to be winding uniformly, if there are any soft or unduly hard places due to the web being thin or thick in some positions (or, to be more precise, due to bulk being lower or higher) these will almost certainly be accentuated in the winder and will then cause creasing. In this respect the drum-wound reel-up is better than older types, because the roll can be reeled at tensions closer to those sustained on the winder and defects in uniformity which may become troublesome are more readily apparent. The time-honoured method of detecting hard and soft places is by hitting the roll with the hand or some special implement and sensing how much it yields. Hard places occur where thickness is higher, soft places where it is lower than adjoining regions of the roll; and to correct these variations, the calender air blowers and other methods of altering calender loading are brought into play.

Generally speaking, this traditional method of evening up reeling-hardness across the reel works satisfactorily so long as the degree of correction required to different parts of the roll is not great. In practice most machines go through periods when this is not the case, and due to some fault either in the calenders or further up the machine it becomes a struggle to reel at uniform hardness despite clusters of air blowers full on and concentrated on to one or two particularly bad soft places. This is frequently due in the first place to unevenness of substance and moisture, bad heavy or damp streaks making it impossible to build a uniform roll, but unfortunately even when unevenness of thickness is obviously due to substance and moisture inequalities, it is by no means simple to decide on an appropriate corrective action. Added to these sources of variations in thickness are those originating in the calenders, so it is not surprising that occasionally the dryerman can lose control of the situation. This topic will be enlarged on when dealing with the practical aspects of building a uniform reel in 5C.5 4.

The most systematic approach to this whole problem is to endeavour first to get the substance profile as even as possible, then the moisture profile, and finally to make corrections for uneven thickness across the machine roll by adjusting the calender air blowers; with these three properties uniform it is reasonable to expect that the roll will also be even across the width in respect of finish, strength and other properties, at least so far as it is practicable to make them even, and at the same time the roll

should build up without hard or soft spots so that this problem would also be resolved. In practice there are limits to how far the substance and, particularly, the moisture profile can be evened up so some discrepancies in thickness profile originating from unevenness of these qualities will require correction.

To assist the dryerman to make correction to the thickness profile systematically, it is valuable to display some indication of the quantity of air, and hence the degree of cooling, that is being used in each position across the calender rolls. This also gives early warning if one particular position begins to require too much correction.

Testing the reeling-hardness by hand has a rough and ready appearance about it and an attempt has been made to devise a means of measuring this property once the reel has been thrown out the machine (18). More recently a concrete hardness tester has been adapted for use on machine rolls but as yet there are no operational reports on its use. Though a measure of reeling-hardness on finished reels could be useful as a tool for investigational work and possibly to improve the profile on a long-term basis, only some means of indicating hardness variations while the roll is being built up would be of genuine value to the dryerman. At least one device for this purpose has been marketed but no reports on its accuracy or practical value have yet appeared.

As an alternative to testing reeling-hardness it should be adequate in most cases to consider paper thickness, since evening this up should automatically counteract unevenness of reeling-hardness provided substance is also reasonably uniform. Thickness across the web is readily measured by micrometer or on a sample strip taken off the machine web with one of a number of thickness-profiling devices, but except on paper-board this approach appears in practice to be of limited value for the purposes of regulating evenness on the machine. One reason for this may be that differences in thickness expansion (due to moisture pick-up) from time of extraction from the reel to measurement complicate interpretation of the results especially as the original thickness variations are closely related to the moisture anyway.

A more satisfactory approach to this problem, and one which permits control directly on the machine where it is of most value, would be to use a device which gives a direct measure of the thickness of the web before reeling at a large number of positions across the machine. Several methods of doing this have been suggested and marketed, the most popular depending on amplification of the gap between rotating discs or rolls contacting both sides of the web; more recently the pressure from a series of air jets positioned close to the sheet has been used, the jets either opposing one another on opposite sides of the sheet or suspended across the machine on a beam rigidly connected to a roll over which the sheet passes. The latter system uses small manometers to measure back-pressure of the air and thus lends itself to a form of presentation similar to one that can be used for calender air-blower pressure, thereby permitting a rapid means of assessing the effect that a measured change in calender air pressure has on the paper thickness. Another device uses an electrical

measurement of magnetic permeability in the gap between two sections of a magnetic reactor contacting opposite sides of the paper web; when the cross-web changes in this measurement are used to vary air nozzles directed on the paper (these giving more sensitive response than nozzles on the calender rolls) it has been claimed that considerable improvement in thickness profile is possible (114, 115). As yet, insufficient information is available to indicate whether these devices are capable of withstanding machine conditions. But when this is the case, it may be expected that a valuable tool will be available which, by permitting thickness differences to be readily compared with calender cooling across the machine, should enable the whole business of building an even reel to be placed on a more systematic and reliable basis.

5C.4 2 Regulating the calender cambers

Substance and moisture unevenness across the web are apt to cause thickness unevenness (with the related difficulties due to hard or soft spots) largely in areas of relatively narrow width. It is also quite possible for the calenders to be a source of relatively narrow unevenness, especially if localized wear of calender rolls has occurred over a period due to some relatively permanent difference in the paper web itself, but by and large, lack of thickness uniformity directly attributable to the calenders exhibits itself over larger regions. The most common unevenness from calenders is roughly symmetrical about the centre, i.e. the result of incorrect camber magnitude or shape, bearings heating up, incorrect loading, etc.; but also it may happen that loading or roll wear is greater one side compared to the other. Such deficiencies show up as a tendency, for example, for the edges of machine rolls to reel hard compared to the middle (producing wrinkling from the edges towards the middle), or for one side to reel harder than the other, producing spasmodic creases running right across the sheet.

Attaining an even pressure in each nip of a calender stack is a many-sided problem. The shape of the camber must make allowance for the journal overhang, shear deflection of the roll, and the end-effects of temperature variation; (using a straightforward circular cam to impart the shape on a grinder is apt to exaggerate the camber between 10 per cent. and 20 per cent. of the roll length in from both ends, causing soft spots in these positions). The magnitude of the camber must be adequate for the weight of the rolls and the load, if any, applied to the top of the stack. The nips must be horizontal otherwise the paper will pull unevenly from one to the next. These are the broad requirements, but to solve them creates many headaches in the mill, especially when furnishes contain abrasive particles (groundwood and some loadings) which cause calender rolls to wear rapidly.

A general discussion of the questions of camber shape and magnitude has already been given in 4C.3 1. The same principles apply to calenders and it is not proposed to develop these any further; for an excellent detailed survey of the subject, reference should be made to an article by Stone and Liebert (65). Regarding the necessity to achieve horizontal nips, theoretically the position is quite clear: all necessary camber should go on

the bottom or king roll, and if the stack is loaded an appropriate camber is also needed on the top roll. In practice it is often thought advisable, especially for heavy and wide stacks, to distribute a small amount of the camber (1 or 2 thou.) on to the queen roll (second from bottom) where its effect is of course double that of the same camber on the bottom roll. Other intervening rolls should not generally be cambered.

Even following these precepts, after grinding a new stack of rolls to the cambers normally found suitable it can happen that the fit is poor. Some mills try to prevent this occurring by changing only one or two rolls at a time, spreading the process for the whole stack over a number of weeks or months; this has much to commend it except that barring patterns and other deficiencies in the old rolls are liable to transfer to the new. For this reason, when roll-changing is staggered it is important for the period involved to be quite short (say no more than four weeks); it is also appropriate that the changing procedure is repeated at frequent intervals on a planned-maintenance basis. Checking the caliper of the larger rolls of the stack whenever possible, and the compilation of wear curves, as discussed in regard to press rolls, can assist in determining the correct camber and the desirable frequency of changing.

When changing the whole stack at once, or when one of the cambered rolls is changed, either a light test or one of the other means of checking fit beforehand, such as the B.P.B.I.R.A. technique of passing through a full-width strip of N.C.R. paper, is essential to show up any major discrepancies before the stack is put into use. To be of much use, this check must be carried out with the stack close to normal running temperature, and under these conditions it is difficult to determine quantitatively the correction required to eliminate those discrepancies that are observed. It may be necessary in bad cases to remove one or more rolls for re-grinding off the machine, or it is possible to grind the rolls into a better fit on the machine by dripping down the stack an appropriate abrasive grinding compound. Grinding-in on the machine does not, however, find general favour because every roll then sustains relatively high wear; it is only suitable as a relatively quick means of making minor corrections.

5C.4 3   Temperature variation across calender rolls

The running temperature of calender rolls can vary considerably over quite a small distance, and this of course means that local nip pressure can also vary by a large order. Using a surface pyrometer, Howe and Lambert (61) found differences of up to 50 deg. F. at positions one foot apart, and succeeded in demonstrating (by assuming a simple relationship between temperature and roll expansion) that the total effect down a stack of such temperature differences is closely related to the decrease in thickness and increase in smoothness occurring in the paper at different positions across the machine. In fact, on the machine investigated it appeared that thickness variation across the web at the machine roll largely originated in calender temperature differences, only a relatively small proportion of the variation being attributable to local differences in the paper before entering the stack.

Large temperature differences in calender rolls are probably created

mainly by the self-exaggerating effect of what may initially be only relatively small differences in pressure. This is because a slightly greater nip pressure at some point will cause more heat to be generated, and this in turn will expand the rolls and increase the pressure there still further; equilibrium is only achieved at an even greater nip pressure which causes more thickness reduction in the paper.

It should be the main purpose of the air blowers to correct these temperature differences. Normally, as discussed above, this correction is attempted using subjectively-assessed reeling-hardness variations at the machine roll as the guide, this being the most direct approach to the problem. Though a more systematic method would be to use on-machine thickness profiles to indicate where air is needed, the difficulties of obtaining satisfactory thickness measurements of this nature have so far limited developments in this direction.

An alternative and possibly more practicable approach has been described by Sawyer (108) who measured calender roll temperatures directly, using a non-contacting radiant-heat device known as a radiometer; this is an instrument which has an obvious value for troubleshooting when detection of comparative temperatures is required, though it is probably of doubtful suitability for obtaining accurate absolute readings. Regular traverses across the rolls with this instrument showed that patterns change appreciably, even from day to day, and temperature differences could be great, especially on rolls high in the stack. Temperature of the web was also measured by this technique and variations wider even than the calender rolls were found; this may be due to differences in moisture which will affect the relative transfer of heat. Developing this work further, Sawyer arranged an automatic correction system whereby the temperature profile of a roll as measured by the radiometer was used to alter the volume of cooling air applied by the blowers. This helped to reduce reeling faults in the paper and was considered to be a very useful approach. The main limitation lies in the fact that the temperature of only one or possibly two rolls can be used as the basis for correction; also some thickness variation in the finished paper is definitely due to causes other than calender roll temperature differences, even if the work of Howe and Lambert indicates that the contribution is relatively small, and this system will not correct this. One likely approach is to use the method devised by Sawyer to apply correction for calender roll temperature differences with one set of air blowers, leaving alleviation of defects in the paper from uneven moisture and substance to a final correction of the thickness or reeling-hardness with a second set of air blowers.

5C.4 4 Altering calender stack load

Even with the best set of calenders, the need to change load or the number of nips in order to achieve different degrees of smoothing makes it impossible to avoid camber difficulties at one time or another. Dryermen have devised ingenious ways to correct camber deficiencies, from sticking pieces of emery paper or even machine wire under calender doctors to the use of wedges and jacks to force apart adjacent roll journals. Most of these

methods are self-defeating in that they create extra wear on the rolls in precisely the regions where it is not wanted (for example, heating up an area of the roll by inserting an abrasive material under the doctor will temporarily narrow the gap in the nip and hence alleviate a hard spot, but it will also cause the roll to wear faster at that point, thus tending to increase the gap, and eventually even greater local heating will be required to avoid the hard place reappearing). For this reason such expedients should be avoided completely or used only on a strictly temporary basis. It has been realized for some time that what is needed is a means either of altering effective camber during running or avoiding altogether the necessity for any camber at all. The various methods devised to achieve this end will now be briefly discussed.

If a roll having a particular camber is rotated very slightly horizontally relative to the roll above, this has the result of decreasing the effectiveness of the camber. This can readily be visualized by thinking of two parallel rolls in line-contact along the nip; if one of the rolls is crossed horizontally about the centre point of the nip then contact remains only at that point and elsewhere a gap appears between the two rolls which is progressively greater from the centre out to the edges. To counteract this effect and regain line-contact, a degree of negative camber on one or other roll would be needed. This principle has been used for varying the effective camber on an operating stack (93). The method involves offsetting each queen roll journal in relation to the vertical line formed by the other roll journals, positioning being made precise through a specially-designed electro-magnetic unit. On a relatively large stack, a movement of one inch can give an effective change of 25 thou. in the camber on the bottom roll. When the stack is loaded, compensation also becomes necessary for the top roll and a similar means of movement of the roll journals is needed there.

It is claimed that this technique of crossing rolls is simple and effective, requiring only ordinary standard rolls and anti-friction bearings. More camber than is likely to be necessary must be placed on the bottom and top rolls initially because it is only possible to relieve the effect of camber, not to add to it. It is also possible by moving one journal more than the other to counteract to some extent any tendency for one side of the sheet to be calendered more than the other. One deficiency of the technique lies in the fact that the shape of the camber is effectively changed when rolls are crossed and a profile which initially gives a perfect fit would alter to an elliptical curve that tends to put too much camber nearer the ends compared to the middle of the roll. However, this effect may well not be noticeable in the normal course of operation provided alteration to the amount of crossing of the rolls is kept reasonably small.

A second method of changing effective camber has been reported by Kettering (105) and involves the use of air diaphragms to apply pressure between the journals of adjacent rolls. This represents in effect a systematic application of the favourite practice of wedging jacks between roll journals to relieve the ends and increase the effective camber. A certain proportion of any force applied between journals will offset the weight of journals and bearings and improve line-contact when the normal shape of camber

imposed by a grinder is used, but the main danger in this technique (as with placing jacks between journals) is that it would certainly be used to correct other deficiencies; over a period this could well create heavier wear in the middle, making it necessary to increase steadily the amount of pressure or compensation applied.

Two other methods for camber compensation have the advantage of eliminating the need for putting any camber on the rolls; they can probably accommodate nip-pressure operating changes more easily and automatically, and the absence of camber reduces the necessity for frequent re-grinding and eliminates any effect resulting from micro-slip at the centre relative to the edges (the velocity of the outside of a cambered roll being of necessity greater than at the edges). The first of these is the Küsters 'swimming' roll which employs a stationary centre shaft inside a rotating shell; oil is used in between these two surfaces under sufficient pressure to keep the rotating shell floating about the centre shaft, and whatever the load from above there is automatic compensation at each point of the shell. The 'swimming' roll is of a relatively complicated and costly construction and when used in the normal position at the bottom of a stack it is necessary to arrange the drive on to the queen roll. However, several of these rolls are now operational and a fairly detailed report on their use has been given by Hillman (102).

The other method of avoiding camber ('Accra-nip') uses the principle of roll bending. In this the bottom journals are built out at both ends and, in effect, cantilevered by the application of downward forces outside the bearing supports. This has the effect of bending the roll upward in the middle, rather as a ruler bends upward if it is held at each edge with the thumb on the inside and then pulled down with the fingers; by this means the natural deflection that the roll would take up under its own weight and the load of the rolls above is compensated. With a loaded stack the same principle is applied to the top roll, the force imposed at the journal ends being upward in this case. Stone and Liebert (65) have described how this system functions and have illustrated the precision that is possible by using hydraulic pressure in cylinders to apply the forces on the journal ends. Furthermore, by suitably sizing and positioning the cylinders, it is possible to link the top and bottom rolls in such a way that when a change in running nip-pressure is required this is readily achieved simply by altering the common hydraulic pressure.

5C.5 PRACTICAL POINTS

5C.5 1 Start-up

Drying and calendering conditions at the time the sheet is first fed through must be as close as possible to normal running, otherwise there will be endless delays and frustration as breaks recur and broke piles up and impedes access to the machine. The large thermal capacity of the drying cylinders makes it necessary to heat up gradually from ambient temperature over a period of hours, so steam is let into the dryers (including those for felts) as soon as it becomes available; especially if the system is not

automatic the temperature of the dryers and the flash system should obviously be inspected at intervals to ensure that it is rising steadily. Air vents on the condensate lines or flash tanks are kept open for as long as seems necessary, but to be assured of complete removal of non-condensible gases from the cylinders it is desirable to set each section crawling round as soon as the necessary power can be used; this also prevents the felts getting hot unevenly. When the facility is available, steam is let into the calenders from quite early on, but in any case half-an-hour or so before the machine is ready (earlier if a new bottom or queen roll has been installed) the calenders should be set in motion so that temperature of the rolls reaches near normal. The calenders are usually started at full-speed, and this is best done whenever possible with the rolls lowered rather than by skidding upper rolls on to a stack already running which is liable to cause damage; doctors are cleaned and brought into contact straightaway when the stack is up to speed. The ventilation system and H.V. hoods are also started soon enough to ensure air is available at the normal temperature.

Once the cylinders have been set crawling round prior to feeding through, it is essential for the dryerman to devote some attention to several other parts of the dryers. All doctors must be placed in contact with the dryers and M.G. cylinder, and set appropriately for load, oscillation, etc. Cylinder surfaces, especially M.G., require examination. Grewin nozzles and other air blowers should be felt to ensure there is no blockage, and the monitored temperature and pressure conditions checked to be normal. Felts and Sheehan ropes must be inspected to see that running is steady, the guides working, seams and splices not pulling apart, and the tension gear functioning and set correctly.

When the cylinders are eventually speeded up in preparation to receive the sheet, felt guides and the stretch gear on ropes and felts may need readjusting. The power taken by each section should be checked as an indication of poor bearing lubrication, excessive doctor pressure, or waterlogging; the draws are pre-set to conditions anticipated. Other equipment demanding supervision, such as a dry-end pulper, water damper, sweat roll, M.G. pressure roll, reel-up drum and so forth should form part of a check list to make sure the dryerman gives them the necessary attention. Immediately prior to feeding through the sheet a last-minute inspection of the steam and ventilation system is worthwhile and each cylinder should be felt for signs of waterlogging. The compressor providing air for blowing the tail across the draws should be up to pressure and each blower quickly checked over, and the calender air-blowing fan started. The lubrication system and cooling of bearings, cylinders and calenders requires inspection, though this is usually the job of an engineer.

When the sheet is ready to be fed through the dryers, at an appropriate moment steam pressure in the cylinders is increased to normal operating level (or slightly above, as drainage rate and pressing efficiency is likely to be lower than normal at a start-up, giving a higher moisture content leaving the presses). The importance of getting suitable conditions in the dryers to ensure the web arrives at the end of the section with as near as possible correct moisture content has already been stressed; if sufficient

attention is not paid to this, feeding up can become a nightmare with the dryerman altering the steam pressure violently to counteract the web becoming too damp or dry, then losing control of conditions altogether when the sheet breaks and the process of feeding up must be repeated. A 4 to 6 inch tail may be passed by hand from the last press on to the first cylinder, where it can temporarily pile up on the doctor, and then on through the cylinders; on machines running above 500 or 600 feet per minute a Sheehan rope system is in general use and the tail is blown off the press straight into the ropes, which then carry it through to the end of the dryers. The tail is always followed down the machine by the dryerman and when he sees it is passing smoothly along, the sign is given for the cutter to be brought across to widen the sheet to full-width; should the sheet break, the dryerman is on the spot and immediately signals for the web to be broken off at the press or wire before he begins clearing away the broke. With an M.G. cylinder it is usual to feed over the whole sheet at once. The ventilation system may have to be shut off or air velocities reduced temporarily while the tail is fed through, otherwise it tends to flap uncontrollably and break.

The sheet is doctored off the last cylinder, which is invariably a top one, and to prevent the possibility of the web adhering to the last dry felt and being carried over the top, a series of air nozzles may be installed close to where the felt and dryer separate to blow the tail section down on to the cylinder doctor. After allowing a short period for moisture content of the web to approach its normal value (and in this respect a dry-end pulper under the calenders is particularly beneficial) a new tail is cut, by means of a knife, on the top cylinder and passed or blown under the dancing bar or roll and between guide plates into the top nip of the calenders; on slower, narrow-deckle machines it is possible simply to grab the whole web off the last dryer and either cram it straight into the calender nip or, as is done in some cases, lead it over the top roll and into the nip from the opposite side. The sheet is fed down the calenders by hand, being snapped double into each nip by an acquired flick or simply with the fist held against the roll as far as the nip guard allows, or with a tail the process may be made automatic by means of steel fingers or air blowers on each roll; frequently, immediately prior to threading through the calenders, the rolls are sprayed with paraffin oil or some other lubricant which cleans them and softens any paper that tends to stick or be stamped out. Feeding down the calenders can be a critical operation and on no account must a wad of paper be allowed to jam in the stack causing the rolls to jump, or worse to stop altogether in which case scorching and the appearance of flats are likely.

The tail will normally be carried or blown straight across from the calenders to the reel-up although on fast machines ropes can be used; with a drum reel-up the core is brought into contact with the drum as little before this as possible to prevent roughening up the reel-up drum surface, especially when the roll is damped by sprays on the drums. Alternatively the tail can be widened (by hand or automatically) by taking across the knife on the last dryer so that the full sheet is allowed temporarily to come

off the bottom cylinder roll; then a fresh tail, cut by hand on the bottom calendar roll with a sharp-pointed spike, can be led or blown across.

Once the sheet is reeling satisfactorily the first thing the dryerman must check is the moisture content; unless this is near the correct value, breaks are likely. He must assess how evenly the roll is building up, load the calenders by the usual amount, and make preliminary adjustments to the calender air blowers which should have initially all been off or only part open. As soon as possible the first roll is thrown out to allow cross-width checks on the quality, particularly the substance, to be made. When the machineman has got the substance uniform, and drying and ventilation conditions have settled down, further adjustments to the air blowers will, of course, be necessary. This topic is enlarged upon in 5C.5 4.

The dryerman must also at the first opportunity examine the progress of the web down the dryers. If the web is tending to stick or pick on the first few cylinders, the temperature must be reduced; build-up of dust and fibre on cylinder doctors indicates if picking is occurring and also shows how evenly doctors are in contact with the cylinders. Any tendency to flap in the open draws, especially at the edges, should be remedied before creasing or turned-over edges occurs; correct alignment of cylinders and felt rolls is important in this respect, and hot-air nozzles require careful adjustment. Draws are usually altered visually to give correct tension: if slack the sheet tends to wrinkle and fold over, if tight to crease lengthways. Spreader bars or expander rolls should spread out the sheet uniformly and smooth out any unevenness of pull. The steam and flash system should be inspected as soon as practicable, attention being paid particularly to the pressure differential across each bank of cylinders. Felts also require inspection and movement of the guide roll and stretch gear should be positive but slight.

5C.5 2 Shut-down

Procedure for shutting down the drying section and calenders for a scheduled shut is relatively straightforward. The sections are brought to a stop as soon as the sheet has run out and the ventilation system, H.V. hood, and steam supply to dryers, felt dryers, and calenders turned off. Loading on M.G. pressure roll, breaker stack, and calenders is relieved and for a lengthy shut each calender roll, particularly the bottom and queen rolls, should be supported separately or at most in pairs on the journals to avoid the possibility of flats appearing; the rolls may also be lubricated with paraffin. Felt tension is slackened, doctors removed from contact (especially on calender rolls), hoods raised, and other parts of the system, condensate pump, water in spray damper or sweat cylinder, the calender air cooling system, dry-end pulper, and so on are attended to as necessary. An M.G. cylinder is usually kept rotating slowly during a long shut to avoid stressing the dryer.

Felts and ropes are now inspected for flaws, for which it is necessary to crawl the cylinders round. At the same time the state of the drying cylinders is assessed and it may be necessary to remove scale and fuzz from several

cylinders, particularly at the wet-end, by using suitable scraper-knives. One or more cylinders may be opened up for examination of siphons and the general condition inside. Calender rolls are examined carefully for marks and roughness, or signs of barring on the surface; calenders usually generate a considerable amount of dust so cleaning, preferably by vacuum cleaner, requires careful attention. All pieces of broke must be cleared away from the dryers either by hand, or by hooking or (when gears are completely enclosed) by blowing out with compressed air; doctors and associated trays on top cylinders are cleaned out with a long-handled brush or vacuum cleaner.

During a wet-end break of any length, a similar procedure is necessary to when the machine is being shut. The drying cylinders may be kept rotating, but calenders should definitely not be allowed to run without paper for too long because of the heat generated by the contact that takes place between rolls. Reduction of the steam supply for a break has already been discussed. An H.V. hood is not usually turned completely off and allowed to cool, but normally the heat supply is greatly reduced and the fans allowed to idle; in a similar way it may be arranged that the ventilation system is kept warm, though a Grewin nozzle system is often turned off to ease feeding up.

5C.5 3 Changing and running dry felts

There are still several machines using endless dry felts and for these the method of changing is basically similar to wet felts, but can be very cumbersome and time-consuming. Nowadays dry felts are seamed and the procedure for changing them involves slackening back the tension roll, cutting the old felt across at an appropriate position, and roughly stitching an end of the new felt on to the old. The cylinders are then rotated slowly round, the new felt being drawn out of its folds and the old one collected up, and finally the old felt is detached and the ends of the new one pulled square and seamed together. In the event of the old dry felt falling off the machine it is necessary to thread ropes along the felt run and use them to pull the new felt on. Boards and other equipment needed for dry felt changing should, of course, be kept clean and always stored in the same place.

Methods of seaming vary according to the felt material and running conditions. On old, slow machines a linen thread stitch can suffice, while on faster machines split copper rivets may be used in several staggered rows (this is apparently particularly suitable with asbestos felts where seams pull out easier than with cotton felts). Other seaming methods involve glueing or cementing the two ends (popular with synthetic felts) and the specially-designed clipper seam which joins together alternate metal loops placed on each end. With all except the last method which leaves a small gap between the two ends of the felt, a lap is formed of one end over the other in such a way that the trailing end is on the outside. The choice of seam and the skill with which it is put together are very important, as a large proportion of downtime originating from dry felts is caused by seams pulling apart to

make a large hole, or completely breaking in two. It is for this reason that careful and frequent inspection of the seam is essential.

A new felt must be started with care, and is first slowly crawled round to check that it is pulling evenly and the seam is holding. The tension is then steadily increased, but before the section is brought up to speed the guide and tension gear are inspected, the felt edges watched for signs of un-ravelling or soiling, and a check is made that all felt rolls are turning al-right. When full speed is reached the guide is again checked, and when of the automatic variety it can be brought to a central working position by means of a hand guide roll, following the well-known principle that the felt moves towards the side of the roll it touches first. Alternatively the stretch roll is used to adjust the position of the felt, in which case the felt tends to move to the side that is slackened off (this being the side the felt first contacts); however, this will also cause the seam to pull ahead on the slack side due to shortening of the run. Ideally, the seam should keep perfectly straight across the machine due to the rigidity of the felt, but if it shows signs of leading at one edge this is an indication that a roll is out of align-ment. For a more detailed discussion of this topic reference should be made to an article by Woodside and Macmillan (119).

Once paper is drying, the stretch roll and tension gear must be carefully watched. There should always be a steady, positive motion occurring if the automatic tension is working correctly; otherwise when the gear is sluggish, excessive tension can easily build up, threatening the seam and causing the felt to become baggy in places. Shrinkage of a dry felt as it becomes damp is common and under these conditions, especially with a new felt, the stretch roll position is inspected regularly for some hours; occasionally a felt shrinks excessively causing the edges to overlap the roll ends and get oily, or it may have to be removed as the stretch roll reaches the end of its travel and tension becomes so excessive that roll bearings get overheated. Other dry felts stretch when new and if this becomes excessive it may be necessary to stop the machine, cut across the seam, and re-seam with a piece taken out. In very bad cases the felt may have to be removed al-together because its deckle becomes too narrow to cover the paper. When a new dry felt is joined up, experience of the behaviour of similar types allows the position of the stretch roll to be appropriately selected when the ends are seamed.

Running of dry felts usually presents little difficulty unless the felt is accidentally damaged, or if the web passes under a cylinder doctor during a break and finishes up in a thick wad which permanently bulges the felt. At best this is liable to cause paper coming under the bulge to be held off the cylinder by a steam pocket, creating a damp, stretched patch; but if the bulge is really bad, as it passes over the stretch roll, the felt will be liable to run into two short diagonal creases. Wrinkles in dry felts, especially newer ones of the plastic fabric types, are also caused by felt rolls being out of alignment (to check this involves taping round cylinders and rolls at both ends and also measuring diagonally) or by the stretch roll being tighter in movement or binding at one or both sides; a temporary remedy is to slacken back the side to which a diagonal wrinkle runs. Persistent moisture

540

differences across the sheet can affect a dry felt by causing it to be damper, and of different length, in one position across the machine compared to another.

5C.5 4 Building a good roll

A good measure of the skill of a dryerman in his job is the quality of the rolls he produces from the machine. The evenness of reeling-hardness across the web, absence of obvious shade differences on the roll which betoken lack of uniformity in moisture and calendering, absence of hair creasing or cuts, and evenness of the edge of the roll, all these are to the dryerman what even substance, good formation, and (in general) lack of two-sidedness are to the machineman: a general comparative test of the control and understanding he has of the machine.

The business of building a good reel has been discussed in several places already. It depends basically on maintaining a uniformity across the web in respect of substance, moisture, and thickness. If, in addition, an even tension is held in the draws, alightment of rolls is correct, and the reeling pressure is kept steady, then a really satisfactory roll is certain to be produced.

The job of obtaining an even substance across the web is the machine-man's, but all too often he relies on the dryerman to indicate to him that the weight at some place across the reel appears wrong. This comes about, for example, when as much calender air as possible has been directed on to some soft spot and still fails to remove it; the dryerman may then ask the machineman to tickle up the substance in that region to try to correct this. Unfortunately this does not always prove to be the remedy and the soft spot can be worsened. It all depends on the origination of the low thickness causing the soft spot, and this can be the substance, moisture, calenders, or any combination of the three.

To illustrate the complexity of the situation, consider the possible sources of a soft spot which appears at some place across the machine roll. This may, in the first place, be due simply to the calenders being too hot in that region (camber too great, overheated bearings at the edges, poor doctor application, etc.). The correct remedy in this case is to use air from the calender blowers to cool the appropriate position down. On the other hand, the soft spot may originate from the paper being too damp at that particu-lar position across the web when entering the calenders (uneven press action, worn dry felt, cylinders scaled up, etc.); the calenders then have more compressional effect on the damper region, thus producing the soft spot. To remedy this correctly would necessitate a means of correcting cross-web moisture in the drying section. Thirdly, the substance may be light due to a ridge in the wire or bad adjustment of the slice; this in itself could produce a tendency towards low thickness and a soft spot, though low substance would be associated with comparative dryness at the reel-up and this should counteract the effect to a greater or lesser extent. The remedy for uneven substance obviously lies at the slice. Any combination of these three basic sources could produce the soft spot, so more than one correction may well be needed.

It should be observed in this context that an associated complication is created by uneven shrinkage of the paper at different points across the web. If one position should dry quicker than the rest of the web, this causes it to stretch due to the greater restraining force it experiences and has the effect of producing softness in the machine roll; this is irrespective of the fact that the region may well retain lower moisture content through to the calenders which should partly offset the softness. This situation is often found at the edges (particularly the front edge), where on machines running well-beaten grades, slackness can be very troublesome and in extreme cases causes a sort of wavy fluting on the roll edge; it originates from excessive stretching due to quicker drying at the edges for which, as discussed earlier, no really satisfactory remedy yet exists. Slack edges as such can, however, be overcome using spreader bars or expander rolls to help stretch the middle up to that sustained at the edges, but often the substance is run permanently heavy at the edges to offset the more rapid drying.

While the various possible causes of a soft spot are thus well-known, identifying the source in any particular case is practically impossible without instrumental aids. Generally speaking the dryerman relies simply on the adjustment at the calenders to even up the reeling-hardness, and when this fails he turns for assistance to the machineman. As already stated, the most systematic procedure is first to adjust the substance as evenly as possible across the web, then the moisture, and finally use the calender air blowers to even up reeling-hardness. Only if the air blowers fail to correct sufficiently under these conditions, can temporary adjustment of the substance (necessarily reducing uniformity of this property) be justified to keep the machine running; if this procedure is followed, it is evident that the calenders are more readily identified as the source of the trouble and the fault can be remedied at the first opportunity. To achieve a method of working along these lines requires accurate information about the cross-machine substance and moisture profiles and, above all, a means of correcting moisture differences across the web at least as adequate as is available on most machines for correcting substance. The state of development of each of these desirable features has already been discussed in detail and it is evident that there is a long way to go. In the meantime the dryerman must work as best he can with the adjustments available to him, plus his knowledge of the idiosyncrasies of the machine.

Differences in reeling-hardness due to uneven nip pressure at the calenders are usually not so local and random in nature as those originating from lack of uniformity of substance and moisture. Because of this an isolated soft or hard spot is most likely due to lack of uniformity in moisture and substance, and comparison with obvious differences in dampness of the roll can provide some clue as to the origin of the unevenness (it is, of course, not difficult to detect fairly damp regions across the roll by feeling the web with the palm, or by viewing the roll at an angle when damp streaks appear darker). If a soft spot coincides with a damp region, there is a strong likelihood that the cause of softness is in the drying or pressing. On the other hand, if the soft spot does not appear any different in moisture content from the rest of the web, it is more likely that low substance in that

region is the cause. A similar tendency shows up with hard spots: if moisture appears normal, the substance in that region is probably heavy. However, there is a complication in that, as the dry-weight of a straight-forward heavy streak grows, a point seems to be reached where the web becomes so much damper that reduction in thickness at the calenders, due to the added moisture, more than offsets any increase in thickness resulting from the additional fibre; when this happens the substance unevenness is shown up by a soft spot, not a hard one, and the interpretation likely to be placed on the coincidence of softness and dampness (that drying is at fault) becomes incorrect.

The close association that substance and reel-up dampness have on reeling-hardness makes it imperative that the machineman and dryerman co-operate closely in their efforts to produce good rolls and correct cross-web faults at the reel-up. The machineman always indicates when any changes of speed, substance, furnish and so on affecting the overall machine conditions are due, but keeping the dryerman in touch at times when it is necessary to make any important alterations which may affect the cross-web uniformity, is equally important. If, for instance, the machineman alters one or more of his jackscrews to change the substance at some place across the machine according perhaps to the appearance of the dry-line or couch take-off line, when the alteration has been completed he should warn the dryerman to keep an eye on the appropriate position. The same applies to other running adjustments likely to alter the cross-web evenness: depending on how good the machine system is, this could cover anything from changing press load to altering head at the slice. Experience is the only guide in these matters. Neither should information be one-way, for the machineman generally has to rely, in his efforts to achieve uniform substance across the roll, on test results which do not take account of moisture difference; hence the dryerman should always indicate the exist-ence of damp regions, and inform the machineman if he has altered drying conditions to an extent which could have an effect on the moisture content at different places across the web.

5C.5 5 Checking the dryers and calenders during running

Apart from inspecting the dry felts and ropes, and endeavouring to build a satisfactory machine roll, the dryerman must constantly be checking over many other parts of the drying section and calenders. An engineer is normally assigned specifically to inspect the steam supply, flash system and condensate tanks, the individual drives, the ventilation and hood system, and the bearing lubrication and cooling, but it is nonetheless the dryer-man's ultimate responsibility to ensure these are behaving correctly and catering adequately for the needs of the sections.

On a tour of inspection the dryerman will first examine round the calenders, feeling the journals and air nozzles, and looking at the doctors to see that the fit is even, then wiping them across with a rag. As he walks alongside the dryers, each cylinder should be touched as a rough check against waterlogging; the surfaces are inspected and if rings are forming, the doctors are moved laterally or weighted. Grewin nozzles are tested in

case of blockage. The surface of an M.G. cylinder and the various doctors are given particular attention, and evenness of the take-off line from the cylinder surface often shows up irregularities. Particular note is taken of the line of the sheet in the open draws between cylinders: drive irregularities, dryer eccentricities (which should be observable by eye or by a regular change in the tone as the dryer rotates), and misalignment of rolls due to gradual wear of the bearings, are some causes of an uneven pull which shows up a regular flapping of the whole sheet; but more commonly, flapping occurs only at one or other edge and is a product of uneven drying at the edge or poorly directed air blowing from nozzles into the pockets. Dispersion of steam in the cylinder pockets should be steady and reasonably even across the dryers. Towards the wet-end, the cylinders are looked over for any signs of being too cool and sweating, or too hot, in which case a rapid build-up of fibre dust is observed in the top doctor trays as the surface of the sheet is picked.

Returning down the back of the machine, the dryerman inspects the load on each section and the draw positions, and notes any fluctuation indicating that running is not so smooth as it should be. The flash and condensate system should be functioning satisfactorily, with liquid-level gauges between marked limits and registered pressures within the usual range; fluctuations in the flash system resulting from surging of pumps or build-up of condensate in the cylinders should be noticeable from the various indicators, especially when the drive is being affected. Ventilation instruments are checked, and any steam leaks from dryer journals noted.

Breaks in the drying section are caused mainly by the action of excessive tension on weak places in the web. Excessive tension occurs when the draw is uneven or if shrinkage forces within an individually-driven section become too great; machine-direction strain lines can generally be seen when tension is too high in any particular draw. Weak places in the sheet originate from wet-end defects (pitch or slime spots, rough edges, light substance streaks, etc.) which have survived and possibly been weakened by the couch and press draws. Other weaknesses may be caused in the dryers themselves if some regions remain very damp as the remainder of the web dries. Such damp regions can occur if a piece of hard dirt is embedded in the sheet (this appears to prevent the felt pressing evenly on the paper surface giving an area round the particle which dries slower) or from condensation dropping, cylinders sweating, or if the felt does not give an even pressure on the web (bulges caused by damage or poor running in, poor seams, holes, etc.).

Certain parts of the drying section are more prone to breaks than others: the first few cylinders where the web, especially when too damp, may tend to stick to the dryer surface and blister if the temperature is too hot or the cylinder dirty, is a frequent location of breaks; also susceptible are the cylinders towards the end of the section where the shrinkage rate is relatively great and the web tension is more sensitive to changes in beating and making conditions. It is useful for the dryerman to keep a record of the number of the dryer which immediately precedes the point where each break occurs; over a period this record shows up the positions which give

most trouble, and serves to indicate that attention is needed to such things as altering the flash system to change the temperature of the first few cylinders, checking the alignment of one or more cylinders and felt rolls, making provision for more draws, and so forth.

Breaks in the calenders are almost entirely due to defects in the web which can have originated anywhere down the machine. A very damp place of relatively small area may well survive the dryers, but when the calenders are reached this region of the web becomes distorted into a light patch trailed by corrugations giving a miniature crêping effect, or it may be stamped out completely to produce a hole. Creases or strained regions of the web readily fold over in the calenders to produce a permanent cut in the paper which may tear apart where the web leaves the bottom nip. A regular transparent spot at one point of the web is usually caused by a piece of fibre or pitch adhering to a calender roll and passing under the doctor. The draws to and from the calenders are particularly liable to fluctuation due to changes in load caused by cylinders waterlogging, belts slipping, and so forth, and also due to changes in tension as the machine roll builds up; this makes these draws very sensitive to any defects in the web. Dust can be a problem at the calenders but can be reduced by running at a higher reel-up moisture content, avoiding spreader bars in favour of expander rolls, and employing vacuum doctors to suck the dust away.

Fortunately, on most machines, more defects in the paper web actually survive intact through to the reel-up than cause a break; if this were not the case few paper machines would make any profit. Many of these defects are admissible in the saleable paper, provided they are relatively small, but many must be removed before the customer takes delivery. When paper is destined to be cut up in sheets and sorted either by hand or machine, this presents little difficulty; but when the paper is for sale in roll form it is important that as many defects as possible are removed at the winder. As this runs at greater speed than the paper machine, it is obviously not so easy for the winder crew to spot any holes, calender cuts, damp blotches, and so forth as it is for the dryerman who can observe the sheet travelling down the calenders and across to the reel-up. All good dryermen, even when relaxing and talking, do so facing the reel-up so that their eye catches any defects and they can then mark the side of the roll or insert a tab to ensure closer inspection and possibly removal at the winder. A roll with a great many tabs sticking out of it does not by any means condemn a dryerman for not remedying some recurring defect, which may not anyway be within his power; rather it shows up consideration for his colleague on the winder, even though this man may not regard it that way when he sees the roll.

REFERENCES

(1) Attwood, B. W. and Smith, S. F.: 'An Experimental Machine for Investigating the Drying Process.' Proc. Tech. Sec. 31, 3, 577. November, 1950.
(2) Smith, S. F.: 'Dried-in Strains in Paper Sheets.' Proc. Tech. Sec. 31, 1, 107. February, 1950.
(3) Arlov, A. P. and Ivarsson, B.: 'Effects of Draws and Felts on Mechanical Properties.' Svensk. Pap. 54, 21, 729. November 15, 1951.
(4) Rance, H. F.: 'The Influence of Papermaking Variables upon Sheet Characteristics.' Proc. Tech. Sec. 33, 1, 173. February, 1952.
(5) Jordan, J. C.: 'Paper Mill Ventilation with Closed Hoods at Iroquois Falls.' P. and P. Mag. Can. 54, 3, 253. Convention Issue, 1953.
(6) Lukianovitch, S.: 'Moisture Control with Closed Hoods.' P. and P. Mag. Can. 54, 10, 126. September, 1953.
(7) Smith, S. F. and Attwood, B. W.: 'Paperboard Drying Investigations by Means of an Experimental Dryer.' TAPPI 36, 11, 481. November, 1953.
(8) Chalmers, G. J.: 'Performance Testing the Dryer Section of a Paper Machine.' P. and P. Mag. Can. 55, 3, 326. Convention Issue, 1954.
(9) Cooke, B. D.: 'The Behaviour of Condensate and the Operation of Dryer Siphons.' P. and P. Mag. Can. 55, 7, 119. July, 1954.
(10) Jordan, J. C.: 'Report on Closed Hood Installations at Iroquois Falls.' P. and P. Mag. Can. 55, 3, 229. Convention Issue, 1954.
(11) Montgomery, A. E.; 'Variation of Drying Rate of Individual Driers Through the Drier Section.' TAPPI 37, 1, 1. January, 1954.
(12) Nissan, A. H.: 'Functions of the Felt in Water Removed on the Papermaking Machine.' TAPPI 37, 12, 597. December, 1954.
(13) Rance, H. F.: 'Effect of Water-Removal on Sheet Properties.' TAPPI 37, 12, 640. December, 1954.
(14) Brecht, W. and Pothmann, D.: 'The Effect of Tension During Drying on the Behaviour of Paper.' Das Papier 9, 13/14, 304; 17/18, 429. 1955. (In German.)
(15) Carlander, A.: 'Development of Continuous Thickness Measurements on Paper Machines.' Svensk Pap. 58, 16, 578. 1955. (In Swedish.)
(16) Carlander, A. T. and Jordansson, L.: 'Examination of a Surface Pyrometer for Measuring Drying Cylinder Temperature.' Svensk Pap. 58, 17, 616. 1955. (In Swedish.)
(17) Knowles, M., Mardon, J., and White, R.: 'Some Observations on Drying on Yankee-type Cylinders. Part III. Air and Heat Balances in the M.G. Hood.' Proc. Tech. Sec. 36, 1, 129. February, 1955.
(18) Mardon, J., Gavelin, G., and Logan, K. C.: 'The Effect of Some Machine Characteristics on Paper Uniformity.' P. and P. Mag. Can. 56, 3, 275. Convention Issue, 1955.
(19) Nissan, A. H. and Kaye, W. G.: 'An Analytical Approach to the Problem of Drying of Thin Fibre Sheets on Multicylinder Machines.' TAPPI 38, 7, 385. July, 1955.
(20) Rogers, W. A. W. and Webster, G.: 'Measurement of Moisture in a Running Dry Felt,' P. and P. Mag. Can. 56, 3, 241. Convention Issue, 1955.
(21) Brecht, N., Gerspach, A., and Hildenbrand, W.: 'The Influence of Drying Tension on Some Paper Properties.' Das Papier 10, 19/20, 454. 1956. (In German.)
(22) Dreshfield, A. C. Jr. and Han, S. T.: 'The Drying of Paper.' TAPPI 39, 7, 449. July, 1956.
(23) Lippke, P. and Rau, W.: 'The Measurement and Control of Moisture with Hygrotester Instruments.' P. and P. Mag. Can. 57, 3, 252. Convention Issue, 1956.
(24) Nissan, A. H.: 'A Theory of Drying of Sheet Materials using Heated Cylinders.' Chem. and Ind. 13, 198; and J. Textile Institute 47, T48. 1956.

(25) Soinenen, M.: 'On Paper Drying Theory.' Paperi ja Puu **38**, 10, 491. October. (In Finnish); also Paper Trade Journal **142**, 19, 36. May 12, 1956. (In English.)

(26) White, R. E.: 'Residual Condensate, Condensate Behaviour, and Siphoning in Paper Driers.' TAPPI **39**, 4, 228. April, 1956.

(27) Bell, J. R., Robinson, W. F. E., and Nissan, A. H.: 'The Rôle of Woollen Felts in the Removal of Water in the Drying Section of a Paper Machine.' TAPPI **40**, 7, 558. July, 1957.

(28) Maynard, C. E. G. and Newman, J. A. S.: 'The Prevention of Machine Shrinkage and its Effects on Moisture Expansion.' TAPPI **40**, 7, 177A. July, 1957.

(29) Preston-Thomas, H. and Dauphinee, T. M.: 'Some Factors Affecting Drying on Paper Machines.' P. and P. Mag. Can. **58**, 5, 159. April, 1957.

(30) Snider, E. H.: 'Newsprint Drying Questionnaire Summary.' Canadian Tech. Sec. Proc. p. 166. 1957.

(31) Wultsch, F.: 'Factors Affecting the Smoothness of Paper.' Allg. Pap. Rund. **12**, 607. 1957. (In German.)

(32) Bowden, J. M.: 'Dry Felts. Review of Dry Felts at Present Available and Results found from their Use in the Manufacture of Fine Paper.' Proc. Tech. Sec. **39**, 2, 235. June, 1958.

(33) Brecht, W. and Heyn, D.: 'The Smoothness of Calendered Paper and its Dependence on Atmospheric Humidity.' Woch fur Pap. **86**, 23/24, 1037. 1958. (In German.)

(34) Hopkins, L. F.: 'A New Drying Cylinder Surface Temperature Thermometer.' Proc. Tech. Sec. **39**, 1, 11. February, 1958.

(35) Janson, L. and Nordgren, B.: 'Drying of Paper on Felt Covered Cylinders.' Svensk Pap. **61**, 19, 834. October 15, 1958. (In Swedish.)

(36) Jepson, M. D.: 'Some Applications of Forced Convection Drying in the Paper Machine Industry. World's Paper Trade Review **150**, 25, 2179. December 18, 1958.

(37) Preston-Thomas, H.: 'Uniformity of Drying Across a Sheet.' P. and P. Mag. Can. **59**, 2, 73. February, 1958.

(38) Race, E.: 'A Machine for Determining the Influence of the Properties of Felts on the Drying of Paper.' Proc. Tech. Sec. **39**, 2, 215. June, 1958.

(39) Bhargava, R. L. and Robertson, J. H.: 'Infra-red Drying of Paper.' TAPPI **42**, 5, 385. May, 1959.

(40) Brauns, O. and Ponton, S.: 'Drying of Paper on Felt-covered Cylinders. The Importance of the Felt for Transport of Heat and Water.' Svensk Pap. **62**, 7, 245. April 15, 1959. (In Swedish.)

(41) Brecht, W.: 'The Behaviour of Papers when their Moisture Content Changes.' Parts I and II. Das Papier **13**, 7/8, 130; **13**, 9/10, 201. April, May, 1959. (In German.)

(42) Brecht, W., Raderer, P., and Weitzel, W.: 'Tendency of Paper to Curling.' Das Papier **13**, 11/12, 237. June, 1959. (In German.)

(43) Campbell, J. E. and Hughson, G. D.: 'Improvement of Moisture Profile by Dryer Insulation.' P. and P. Mag. Can. **60**, 3, T-77. March, 1959.

(44) Daane, R. A.: 'An Experimental Study of Some Drier Drainage.' TAPPI **42**, 3, 208. March, 1959.

(45) Eisele, K. M.: 'Infra-red Radiation Applied to Paper Drying.' P. and P. Mag. Can. **60**, C, 151. Convention Issue, 1959.

(46) Hill, L. E. Jr.: 'Minton Vacuum Driers.' TAPPI **42**, 5, 375. May, 1959.

(47) Ponton, S.: 'Drying of Paper on Felt Covered Cylinders.' I. 'A Comparison of Different Types of Felt.' Svensk Pap. **62**, 19, 692. October 15, 1959. II. 'A Comparison Between Two Wool Dry Felts of Different Weight.' **62**, 20, 749. October 30, 1959. (In Swedish.)

(48) Preston-Thomas, H.: 'Recent Studies in Paper Drying.' P. and P. Mag. Can. **60**, 1, T-17. January, 1959.

(49) Race, E.: 'Experience in the Manufacture and Use of All-Synthetic Drier Felts.' TAPPI **42**, 10, 827. October, 1959.

(50) Barnscheidt, N. and Schädler, M.: 'Removal of Condensate from Drying Cylinders.' Das Papier **14**, 10a, 600. 1960. (In German.) Summary in Paper Technology **2**, 2, 120. April, 1961.

(51) Chapman, J.: 'General Factors Concerning M.G. Operation.' Paper Technology **1**, 1, 33. February, 1960.
(52) Glynn, P., Jones, H. W. H., and Gallay, W.: 'Drying Stresses and Curl in Paper.' Canadian Tech. Sec. Proc. p. 378. 1960.
(53) MacLaurin, M. I.: 'New Instruments for Control of the Paper Machine.' Paper Technology **1**, 4, 381. August, 1960.
(54) Nissan, A. H. and Hansen, D.: 'Heat Transfer and Water Removal in Cylinder Drying.' I. 'Unfelted Cylinders.' TAPPI **43**, 9, 753. September, 1960.
(55) Schoonen, J. P.: 'The Effect of Filming-Amines on Heat Transfer in Paper Drying Cylinders.' Paper Technology **1**, 4, 373. August, 1960.
(56) Smith, B. W.: 'Scanning Basis Weight and Moisture Gauge Systems on Paper Machines.' TAPPI **43**, 3, 226. March, 1960.
(57) Burgess, B. W.: 'The Drying of Web Materials.' P. and P. Mag. Can. **62**, 6, T-303. June, 1961.
(58) Gardner, T. A.: 'Performance of Slotted Orifice Air Dryers.' P. and P. Mag. Can. **62**, 6, T-327. June, 1961.
(59) Gardner, R. C. and Church, F.: 'The Automatic Control of the Transverse Moisture Profile of a Paper Web.' World's Paper Trade Review **156**, 9, 748. August 31, 1961.
(60) Harrison, G. A.: 'An Interim Report on a Sectional Performance High Velocity Hood Installation.' P. and P. Mag. Can. **62**, 3, T-205. March, 1961.
(61) Howe, B. I. and Lambert, J. E.: 'An Analysis of the Theory and Operation of High Speed Steel Roll Calender Stacks.' P. and P. Mag. Can. **62**, C, T-139. Convention Issue, 1961.
(62) Hurm, R. B.: 'Principles of "On the Machine" Moisture Measuring Systems. TAPPI Project 775.' TAPPI **44**, 6, 125A. June, 1961.
(63) MacLaurin, M. I.: 'Instrumentation—its Success and Delusions.' Svensk Pap. **64**, 10, 394. May 31, 1961.
(64) Prince, F. J., Wagner, O. R., and Mack, E. S.: 'Radiant-Heating—Its Characteristics, Generation and Application.' TAPPI **44**, 5, 208A. May, 1961.
(65) Stone, M. D. and Liebert, A. T.: 'Crown Control of Paper Calenders.' TAPPI **44**, 5, 308. May, 1961.
(66) Tyler, J. H.: 'Factors Affecting the Thermal Efficiency of Paper Mills and their Influence on Production.' P. and P. Mag. Can. **62**, 3, T-123. March, 1961.
(67) Whittaker, J. D.: 'A New Forced Convection Drying Hood.' P. and P. Mag. Can. **62**, 1, T-11. January, 1961.
(68) Wultsch, F.: 'The Effect of Calender Rolls on the Quality and Printability of Paper.' Woch. fur Pap. **89**, 4, 143. 1961. (In German.)
(69) Brauns, O. and Larsson, T.: 'High-Efficiency Hoods for Multi-Cylinder Drying. Part 2, Machine Experiments.' Svensk Pap. **65**, 12, 488. June 30, 1962.
(70) Brecht, W. and Raderer, P.: 'The Causes of Curling in Papers.' Woch. fur Pap. **90**, 373. April, 1962. (In German.)
(71) Crook, O. M. and Bennett, W. E.: 'The Effect of Humidity and Temperature on the Physical Properties of Paper.' British Paper and Board Industry Research Association. Report No. RA/T/90. February, 1962.
(72) Emerton, H. W., Page, D. H., and Hale, W. H.: 'Structure of Papers as seen in their Surfaces.' Formation and Structure of Paper. Transactions of the September 1961 Oxford Symposium, p. 53. B.P. and B.M.A. Tech. Sec. publication, 1962.
(73) Gallahue, W. M.: 'New Developments in Stiffening and Stabilisation of Paper.' Paper Trade Journal **146**, 40, 35. October 1, 1962.
(74) Glynn, P. and Gallay, W.: 'Further Studies of the Mechanism of Curl in Paper.' P. and P. Mag. Can. **63**, 8, T-418. August, 1962.
(75) Hultgreen, O.: 'Raising Quality and Production through High-Speed Drying.' TAPPI **45**, 6, 178A. June, 1962.
(76) Larsson, T.: 'High-Efficiency Hoods for Multi-Cylinder Drying. Part I, Literature Survey.' Svensk Pap. **65**, 5, 1964. March 15, 1962.
(77) McCaffrey, K. A.: 'Paper Machine Dryer Control with Jet Compression.' P. and P. Mag. Can. **63**, 4, T-237. April, 1962.
(78) Means, J. A.: 'Water Removal by High Velocity Air Hoods.' TAPPI **45**, 6, 527. June, 1962.

(79) Nissan, A. H., George, H. H. Jr. and Hansen, D.: 'Heat Transfer and Water Removal in Cylinder Drying. II Felted Cylinders.' TAPPI 44, 3, 213. March, 1962.

(80) Page, D. H. and Tydeman, P. A.: 'A New Theory of Shrinkage Structure and Properties of Paper.' Formation and Structure of Paper. Transactions of the September 1961 Oxford Symposium, p. 397. B.P. and B.M.A. Tech. Sec. publication, 1962.

(81) Allander, C. and Eneroth, J. M.: 'Heat Transfer when Blowing Through Holes and Slits onto a Flat Surface.' Svensk Pap. 66, 9, 349. May 15, 1963. (In Swedish.)

(82) Blanchard, R. L. et al.: 'The Change of Paper Properties through Machine Calender Stacks.' Part I. 64, C, T-119. Convention Issue, 1963.

(83) Cuffey, W. H.: 'Newsprint Calendar Vibration as it affects Machine-Direction Caliper Uniformity.' P. and P. Mag. Can. 64, 9, T-379. September, 1963.

(84) Fahey, D. J. and Chilson, W. A.: 'Mechanical Treatments for Improving Dimensional Stability of Paper.' TAPPI 46, 7, 393. July, 1963.

(85) Gates, E. R. and Kenworthy, I. C.: 'Effects of Drying Shrinkage and Fibre Orientation on Some Physical Properties of Paper.' Paper Technology 4, 5, 485. October, 1963.

(86) Hendry, I. F. and Newman, J. A. S.: 'Effect of Machine Variables on the Curl of Paper.' Paper Technology 4, 4, 381. August, 1963.

(87) Howe, B. and Cosgrove, J. C.: 'Calender Stack Barring on Newsprint Machines.' P. and P. Mag. Can. 64, 6, T-259. June, 1963.

(88) Hoyle, R.: 'Thermal Conditions in a Steam Drying Cylinder.' Paper Technology 4, 3, 258. June, 1963.

(89) Hurm, R. B.: 'Factors Affecting Dryer Cylinder Uniformity.' TAPPI 46, 9, 531. September, 1963.

(90) Jepson, M. D.: 'Drying Paper on Cylinders with Accelerator Hoods—Principles and Practice.' Paper Technology 4, 3, 268. June, 1963.

(91) Kerler, J. D.: 'Operation of the Ross Sectional-Performance, High-Velocity Hood.' P. and P. Mag. Can. 64, 2, T-53. February, 1963.

(92) Kirk, L. A., Hudson, F. L., and Hearle, J. W. S.: 'Mechanism of Moisture Transfer from Paper to Felt During Hot Surface Drying.' Paper Technology 4, 3, 251. June, 1963.

(93) Kuehn, H. E.: 'Calender Crown Compensation by Precision Control.' TAPPI 46, 6, 193A. June, 1963.

(94) Luckins, J.: 'Theoretical Benefits from New Methods of Drying.' Paper Technology 4, 3, 245. June, 1963.

(95) Mercer, J. D.: 'Operation of the Ross Sectional-Performance, High-Velocity Hood.' P. and P. Mag. Can. 64, 2, T-53. February, 1963.

(96) Pye, I. T.: 'Calender Barring in Newsprint.' P. and P. Mag. Can. 64, 4, T-194. April, 1963.

(97) Robey, L. A. and Webzell, A. B.: 'Steam Supply and Condensate Removal.' Paper Technology 4, 3, 235. June, 1963.

(98) Wahlström, P. B., Larsson, K. O. and Asklof, C. A.; 'Calender Barring, its Mechanism and possible Elimination.' P. and P. Mag. Can. 64, 4, T-265. April, 1963.

(99) Blatchley, C. G. and Stratton, H. J.: 'The Performance of Thermocompressors as related to Paper Machine Dryer Drainage Systems.' P. and P. Mag. Can. 65, 7, T-301. July, 1964.

(100) Gardner, T. A.: 'Minimum Pressure Differentials required for Dryer Drainage.' P. and P. Mag. Can. 65, 4, T-188. April, 1964.

(101) Gardner, T. A.: 'Engineering Aspects of High-Velocity Drying on Paper Machines.' P. and P. Mag. Can. 65, 4, T-191. April, 1964.

(102) Hillman, C. H.: 'Calender Roll Crown Compensation by the Swimming Roll Method.' TAPPI 47, 8, 141A. August, 1964.

(103) Kenworthy, I. C., 'Drying Strains and Shrinkage in Paper.' Paper Technology 5, 4, 259. August, 1964.

(104) Jackson, M. and Ekström, L.: 'Studies concerning the Compressibility of Paper.' Svensk Pap. 67, 20, 807. October 31, 1964.

(105) Kettering, G. H.: 'Calender Nip Relieving.' TAPPI 47, 8, 137A. August, 1964.

(106) Mardon, J., et al.: 'The change of Paper Properties through Machine Calender Stacks. Part II.' P. and P. Mag. Can. **65**, 11, T-481. November, 1964.
(107) Page, D. H. and Sargent, J. W.: 'The Structure and Physical Properties of Paper. Part II The Structure of Paper in Cross Sections.' British Paper and Board Research Association. Report No. RA/T/112. September, 1964.
(108) Sawyer, W. C.: 'The Dynamics of Heat Flow in Paper Machine Calender Rolls.' TAPPI **47**, 3, 145A. March, 1964.
(109) Wahlström, P. B. and Larsson, K. O.: 'Factors determining Condensate Removal.' P. and P. Mag. Can. **65**, 5, T-203. May, 1964.
(110) Attwood, D. and Hitchin, D. F.: 'Control of Moisture Profile with Cross-Control Drying Hoods.' P. and P. Mag. Can. **66**, 1, T-27. January, 1965.
(111) Burnham, L. A.: 'Pocket Ventilating Rolls to optimize Drying.' TAPPI **48**, 7, 82A. July, 1965.
(112) Church, F.: 'Moisture and Substance Control on the Paper Machine.' P. and P. Mag. Can. **66**, 1, T-3. January, 1965.
(113) Cole, E. J., Drapeau, C. I., and Whitney, C. G.: 'New Aspect in the Theory and Use of Calendars on the Machine.' La Papeterie **87**, 1, 30. January, 1965. (In French.)
(114) Kahoun, J. B.: 'The Development of an On-Machine Caliper Profiler.' P. and P. Mag. Can. **66**, 3, T-195. March, 1965.
(115) Kahoun, J. B.: 'System for On-Machine Measurement and Control of Paper Caliper.' TAPPI **48**, 7, 60A. July, 1965.
(116) MacLaurin, M. I.: 'Control of the Final Moisture Content of the Paper Web.' P. and P. Mag. Can. **66**, 1, T-11. January, 1965.
(117) Parker, J. R.: 'Corrugation of Calender Rolls and the Barring of Newsprint.' Paper Technology **6**, 1, 33. January, 1965.
(118) Schaffrath, P. M.: 'New Attachment improves Calender Stack Operation.' Paper Trade Journal, **149**, 47, 57. November 22, 1965.
(119) Woodside, L. M. and MacMillan, H. J.: 'Guiding Felts—Which Way the Right Way?' Pulp and Paper Mag. America **39**, 50, 35. December 13, 1965.
(120) Anon: 'Strengthening of the Paper Web and Dimensional Stability.' Allg. Pap. Rund. **23**, 820. June 21, 1966. (In German.)
(121) Barbour, D. R. et al.: 'Stress Relieving of Paper on the Paper Machine.' P. and P. Mag. Can. **67**, 6, T-292. June, 1966.
(122) Calkins, D. L.: 'The Effects of Siphon Location on Paper Drying.' P. and P. Mag. Can. **67**, 4, T-225. April, 1966.
(123) Jackson, M. and Gavelin, G.: 'The Role of Nip Temperature and Surface Moisture in the Calendering and Supercalendering Processes.' Svensk Pap. **69**, 5, 131. March 15, 1966.
(124) Jender, B. and Gavelin, G.: 'Sheet Moisture Control on Paper Machines with Air Blowing Rolls.' P. and P. Mag. Can. **67**, 12, T-528. December, 1966.
(125) Mardon, J. et al.: 'The Organisation, Carrying Out and End Results of Heat and Material Balances on Papermaking and Coating Machinery.' P. and P. Mag. Can. **67**, 1, T-37. January, 1966.
(126) Mardon, J. et al.: 'Dynamic Consolidation of Paper during Calendering.' Consolidation of the Paper Web. Transactions of the September 1965 Cambridge Symposium, p. 576. B.P. & P.M.A. Tech. Sec. publication, 1966.
(127) Page, D. H., Sargent, J. W., and Nelson, R.: 'Structure of Paper in Cross-Section.' Consolidation of the Paper Web. Transactions of the September 1965 Cambridge Symposium, p. 313. B.P. & P.M.A. Tech. Sec. publication, 1966.
(128) Page, D. H. and Tydeman, P. A.: 'Physical Processes occurring during the Drying Phase.' Consolidation of the Paper Web. Transactions of the September 1965 Cambridge Symposium. p. 371. B.P. & P.M.A. Tech. Sec. publication, 1966.
(129) Parker, J. R.: 'Effects of Dry Pressing on Printing Properties of Uncoated Paper Webs.' Consolidation of the Paper Web. Transactions of the September 1965 Cambridge Symposium, p. 959. B.P. & P.M.A. Tech. Sec. publication, 1966.
(130) Race, T. et al.: 'Hot-Air Blowing Rolls with Conventional Dryer Felts and Open-Mesh Dryer Fabrics.' TAPPI **49**, 9, 59A. September, 1966.
(131) Simmons, T.: 'Condensate Removal on High-Speed Papermaking Machines.' Svensk Pap. **69**, 23, 813. December 15, 1966. (In Swedish.)

PRODUCTION CONTROL

INTRODUCTION

6I In the foregoing Parts the Fourdrinier paper machine has been subjected to detailed examination and an attempt has been made to present information which will be useful to production personnel in their efforts to overcome operational problems and improve output and quality. In this final section, the paper machine will be looked at from a wider viewpoint and treated as the main part of a manufacturing concern, the paper mill, which is required to operate as profitably as possible. Emphasis will, in other words, be on the paper machine as a whole, with particular attention given to methods of monitoring production and quality and to the detection of inefficiencies in the system and assessment of their importance.

These aspects of operating a paper machine come under the general heading of production control and involve examining the process on a longer time-scale than has been considered hitherto. Concern here is with the gathering and analysis of statistics and the presentation of data in a form which can readily be interpreted by those concerned with managing the plant. In the broadest sense, the objective of such data is to point up weaknesses in the production system which, with the aid of various departments in the mill, can then be tackled in a programme of long-term improvement.

This aspect of running the paper machine has of course been implicit throughout the book and has already been discussed in various guises. Better understanding of the process from a proper appreciation of available theoretical knowledge, improved awareness of sensitive spots on the machine, consistent operation and a planned sequence for starting and shutting a machine, proper planning of maintenance schedules, sensible organization of grade changes, the use of instrumentation to guide operatives in maintaining steady conditions, all these in one form or another relate to improving the system. Even more directly concerned are the keeping of careful records of clothing changes, suction box dressing, calender and press roll grinding, and so on.

Of particular importance in any programme of steady improvement is the gathering of data for the purpose of establishing over a long period standards of operation which act as a touchstone to check conditions on some subsequent occasion. The data it is desirable to collect in this way has been detailed under the heading of 'Long-term records' in each section dealing with maintenance. It is important that this information is obtained at times when the machine system is running well and making paper of satisfactory quality (unfortunately this is the precise occasion when the papermaker is reluctant to cause a break); ideally it should be performed on each of the major grades of paper produced. In times of trouble on the machine or serious quality deterioration, the existence of standards which can form a basis of comparison can be invaluable and the expense of taking the necessary tests at intervals and making short interruptions to

production are rapidly repaid. Results obtained from these tests should of course be presented to the production personnel in a manner which allows ready interpretation of changes and trends; in many cases the most appropriate form is a straightforward graph on which, over a period, it may be possible to draw action limits to assist taking a decision whether or not to enquire closer into any sudden change in level.

6I.1 Monitoring machine performance

It is proposed in what follows to treat the subject of production control in two parts. The first part will be concerned with methods of monitoring production, the second with ways of improving it and the means of assessing their significance.

With a piece of machinery as large and complex as a paper machine it is only to be expected that improvements to the process are continually being sought. Many such improvements are the result of overcoming obvious snags and replacing worn out pieces of equipment. In these cases it is usually plain for all to see that a particular course of action is desirable and even, in some cases, imperative. But sometimes there may be other time-wasting equipment and practices that are not immediately evident. How can these be detected?

The answer is by comprehensive and accurate monitoring of time lost in operating the machine. Properly designed records of downtime can indicate the greatest sources of wasted time, and so point the need to concentrate effort in certain spots. For this reason, an essential feature of any paper machine should be the keeping of a systematic analysis covering downtime, speed, production, and efficiency (the latter under various headings). With such records it will be possible to tell just how well progress is being made in improving operation. This alone is a valuable facility, if only to disillusion one when anticipated increases in speed or reduction in broke do not materialize.

Monitoring machine performance means not only keeping a check on the actual quantity of paper produced but also on the quality. This impinges on quality control, a subject that has already been sufficiently written about. In the present context attention will be given more to some broader issues relating to quality control and rejection schemes, and also to the long-term monitoring of quality.

6I.2 Improvement of machine performance

At the root of all improvement is, or should be, the potential financial advantage. Too often this all-important point is ignored, particularly it may be said by technical personnel. Often it is simple to detail the technical advantages of some innovation. But to be valid these must be brought down to hard cash before they can really be justified. Unfortunately this is very often difficult and sometimes impossible to fulfil.

The ability to provide relevant financial data for such assessments is one of the prime advantages of a detailed costing system. The most convenient form this can take seems to be that of standard costing as this lends itself to providing answers to the many questions that must be asked before it is

554

possible to present an economic justification for a particular course of action. To be able to assess whether any improvement is economically valid it must be possible to relate increases in machine speed, reductions in broke and downtime, raising moisture levels in finished paper, and so on to pounds, shillings and pence. Associated with this is the need to be able to determine the actual cost of producing different grades of paper and different substances of the same grade. Too often it is the case that the profitability of different grades, especially when specific requirements create difficult machine conditions or necessitate a prior shut, are known only hazily.

These are the subjects which will be discussed under the general heading of production control. It is surprising how little has been written about this topic and how few references there are in the technical literature. Batch production processes seem to have been given far more attention than continuous processes like papermaking, and unfortunately the methods used in control of batch processes are rarely relevant. It is hoped that the discussion in the following pages will help in some small way to remedy this deficiency.

CHAPTER 6A

MONITORING MACHINE PERFORMANCE

6A.1 ANALYSIS OF DOWNTIME

Checking the downtime occurring on a paper machine is probably the most simple yet useful method readily available to monitor performance. It has the merit of being largely independent of the type of paper made on the machine, and so overcomes the problem of analysing overall machine performance when a variety of grades are made in rapid succession. Also the cost of an hour's lost time can usually be estimated with some accuracy even in mills with only a rudimentary accounting procedure, so it is a relatively simple matter to determine the financial loss resulting from downtime due to different causes.

A really comprehensive downtime analysis has many advantages. It shows up the main sources of interruption to steady production and allows the benefits of any improvement from an alteration made to the machine or to operating procedure to be readily determined. It also, when properly presented, draws the attention of management to deficiencies in the production system and assists in defining areas to which technical resources should be directed. If certain relevant parts of the data are made available in an appropriate manner to machine crews, it is possible that operating discipline will improve. Though in this respect careful consideration of mill labour conditions is needed before publicizing shift-wise comparisons as it is not always either desirable or wise to attempt to inculcate an open competitive spirit. Finally, where a variety of grades is run on a machine an accurate breakdown of time lost in preparation and in running each grade permits more detailed costing figures to be accumulated.

6A.1 1 Collecting information on downtime

The traditional form of report compiled by the machineman or foreman at the end of each shift is completely inadequate for any reliable analysis of downtime. Estimates of lost time from different causes and on specific occasions will almost certainly be inaccurate, and a strong tendency to report fewer breaks and lower times than actually occurred would be an understandable human failing. In cases involving clothing changes or a routine wash-up it is quite likely that a standard time is reported regardless of what actually happened. Nevertheless some sort of report is obviously essential and the form this takes depends on how other data on downtime is obtained.

The simplest method of improving the accuracy of available data is to link to the machine a recorder which clearly indicates the periods when no paper has been passing to the reel-up. This recorder can serve solely to provide downtime data, or may be used in addition for some other purpose, for example to show the machine speed. It is important that all breaks

556

occurring at the reel-up are indicated and this can be arranged in a straight-forward manner by using a photoelectric or ultrasonic web detector immediately prior to the reel-up. In some cases changes in power input to the calender or reel-up can be used for the same purpose, or a micro-switch on a small feeler resting on the web can act as a sensing device. When either of these systems is employed, however, some difficulty can occur at reel changes when flapping of the web inadvertently actuates the break-detector mechanism. Continuous substance or moisture meters are an alternative method of obtaining a record of breaks though, if the instrument heads are removed manually from the web at a break and then replaced when the sheet is up again, there is a likelihood of consistent error in the length of time recorded. In addition to providing a simple record of breaks, a useful facility is to arrange for these to be added together on a total-izing counter. For convenience in checking downtime on different grades, this totalizer can be in two parts, one of which is re-set manually to zero at the start of each grade and logged at the finish.

The breaks shown on such a recorder will vary in length from a blip where the web has broken at the calenders and been immediately fed back, through to the really long breaks where the machine has been shut. A variety of data can be extracted from the record of these different breaks (this is dealt with below) but the most valuable information obviously depends on the ability to relate each break to some specific cause. It is here that the machine report becomes important and must be compiled using the recorder chart as a basis. The recorder should be considered by the machine crews and supervisory staff as an aid to more accurate reporting of downtime, not in any way as a means of assessing their individual performance (hence the reservations with regard to publishing shift-wise comparisons) otherwise co-operation could become difficult to secure. In any event, it is usually only practicable for reasons to be given for breaks which last for some time, say over ten or fifteen minutes, otherwise compiling the machine report becomes a lengthy business.

It is also valuable to know whereabouts on a machine breaks occur most frequently and to compile this information necessitates careful reporting. Elaborate equipment has been devised to do this automatically by using a succession of vacuum switches and photoelectric or ultrasonic web detectors placed at strategic points down the machine to sense when it is operational (14, 15, 17). The signals from these detectors are then fed to a specially-designed data-logging device which produces a simple read-out listing time lost due to breaks in various positions, with cumulative totals over appropriate periods and calculations of operational efficiency for each section. The same signals can of course be used for actuating other opera-tions integral with the machine (couch pit pump started, cutter brought over, etc.) and for giving audible and visual indications of a break.

Whether the expense involved in installing and maintaining such equip-ment is justified depends on the value any individual mill places on having data of such precision available. It is still necessary to report the reasons for breaks occurring, so close co-operation with operating staff is vital. There may also be a danger of accumulating too much information so that

the main points of interest become lost in a sea of figures. On the other hand it is very useful to know the relative proportion of breaks occurring at different positions on a machine, and careful discipline is required if this is to be noted at all accurately by one of the operators. Possibly it is useful to have one or two break detectors at, say, the couch and presses and at a size press or on-machine coater to provide some independent picture of what is happening, and these can be linked to quite simple counting devices. But apart from this an attempt should be made by the operators to list breaks occurring at different positions; in particular, for breaks in the drying section it is useful to note the cylinder immediately preceding each break because this data built up over a period can assist in pinpointing fluctuating and uneven draws, and water-logging cylinders.

An essential feature in encouraging accurate reporting is to design a suitable form for the shift machineman or supervisor to fill in, rather than just expect him to provide the information required in a blank book. Examples of such forms have appeared in the literature (see 9, 12, 14, 15) and must be tailor-made to suit each machine. Broadly-speaking, it is important to keep the demand for details down to a minimum and design the form so that a simple sequence of facts has to be filled in for each break. This would include: time break started and finished (preferably taken from recorder chart); position break occurred (tick in appropriate column); reason for break (again a tick in an appropriate column with a space for miscellaneous reasons); and finally space for notes on grade changes, machine conditions, equipment requiring attention, loss of quality, and so on. In certain circumstances when there is doubt about the cause, it is desirable that whenever possible the ends of breaks are kept for inspection by production supervisors. A sequence of short breaks at the calenders would not be individually listed. An alternative to using a machine report for detailed listing of breaks is to employ a device whereby one of a number of selected causes can be chosen on a telephone type dial which marks the appropriate number on to the recorder chart. This has the merit of making subsequent analysis much easier but cannot completely replace a machine report.

A well laid-out machine report also permits simple clerical analysis, a further asset. It is important, however, that this analysis should always be performed in close association with someone in the production department who understands what is happening and can interpret the reasons given for breaks in a sensible manner. The cause of any doubtful breaks must be discussed with the personnel concerned otherwise friction can develop between the production and other departments in the mill over the basic reason for a break occurring. Often too a particular break can be attributed to a number of causes and some sort of apportionment has to be agreed. On such occasions it is wise to avoid intense post-mortems so long as a reasonable splitting does not strain amicability.

6A.1 2 Analysing downtime data

With a record of breaks occurring on the machine, and a reasonably comprehensive report from the supervisory personnel, it is possible to

accumulate really invaluable information relating to all aspects of performance. The data collected in this way is all essentially long-term and is not usually suitable for checking on day-to-day production difficulties. It is proposed now to discuss the sort of procedure that can be adopted when analysing breaks records, and the type of information obtained. In this respect, much depends on machine conditions and on the length of runs between makings, and what follows is based on the author's experience and must be considered only as typical.

The most practicable arrangement for a breaks recorder is to use a strip chart with a speed of one inch per hour. This is conveniently analysed at weekly intervals and a special rule marked in sixtieths of an inch can be used to determine the length of individual breaks. The chart would first be marked off clearly into shifts, and each shift identified with the appropriate crew (this is particularly important when a four-shift system is used and crews are continually changing their working hours). The number of breaks occurring in each shift is counted, and using the rule the length of time occupied by each break is noted on the chart. Blips on the chart can simply be regarded as a break of one-minute duration. The next step is to compare the breaks record with the machine report and account for all breaks which lasted for longer than some generally agreed period, probably ten or fifteen minutes as mentioned above. With properly prepared working sheets this whole procedure can be made into a perfectly straightforward clerical operation.

From this basic analysis of the chart, a variety of statistics can be produced. Firstly depending on whether the mill shuts at week-ends or is in continuous production, the time taken for starting-up and shutting down or for a scheduled maintenance shut is noted. Likewise the time for grade changes necessitating a shut for washing-up are listed, and also any shuts for routine machine testing and for experimental reasons. A graph showing the week-by-week time for starting-up or for scheduled maintenance shut periods is useful for indicating trends, and also, in conjunction with an arbitrary action limit, can be used by management as the basis for initiating an enquiry into why a particular shut took longer than usual. Averaged over suitable periods, this data is also particularly useful for accounting purposes, especially where a machine runs a variety of grades some of which require more elaborate preparation. For this purpose, to permit accurate costing shuts must be carefully related to the appropriate grade, and if an individual period is excessively long due to some peculiar condition, to avoid unfair bias to the average it is preferable to discount it.

The breaks themselves can be analysed in a variety of ways. One useful and simple indicator of performance is the number of breaks occurring per shift. This is easy to determine, and provided planned breaks for grade changes, maintenance shuts, and machine testing are discounted, and only the figures for full shifts during which the machine has been running are used, then some useful statistics can be obtained for long-term comparison. For instance, the number of breaks occurring during shifts operated by different crews provides a simple basis for comparing performance. In contrast to comparison on a time basis, this has the merit of avoiding bias

559

caused by the chance occurrence of long shuts perhaps for reasons outside the control of the machine crew. Provided a sufficiently long period is chosen (three or six months) then an inattentive and slack crew will gradually accumulate a slightly higher average number of breaks per shift. It is also interesting to observe that on the night shift, irrespective of which crew is working, there are almost always on average fewer breaks. Theories to account for this are left to the reader.

A graph showing the grand average number of breaks per shift from week to week can give a useful indication of general trends. This graph should either be on semi-logarithmic paper, or the logarithm of the number of breaks should be plotted. The purpose of this is to give equal percentage changes the same value (a reduction from 6 to 3 breaks per shift is equally as good as a reduction from 12 to 6).

Breaks lasting for different durations can be grouped into several categories, for example those under five minutes, between 5 and 15 minutes, between 15 and 60 minutes, and over 60 minutes. Summed over a long period, this shows how much time is lost due to breaks in each group and thereby indicates whether, for example, a large number of breaks of short duration occurring in the dryers and calenders is making a greater total contribution to lost time than the occasional long shut for clothing changes or other problems. This sort of analysis sometimes provides unexpected information because it is only too easy to ignore the waste in production caused by a large number of short breaks. The only difficulty in arriving at a realistic assessment of the time lost from short breaks is the limitation in determining from the record chart the length of each break. In practice one minute is the shortest realistic time that can be given for a simple blip, particularly in view of the quantity of paper actually reeled up that is likely to be torn up afterwards when there is a succession of short breaks. An alternative and more accurate approach, suitable when a totalizer is associated with the breaks recorder, is simply to work out the total time lost less the sum of time lost from all itemized longer breaks.

Comparison of the time lost due to breaks resulting from different causes usually yields the most valuable information. With a well-designed machine report in which the reasons for all longer breaks are clearly given, the task of analysing and allocating breaks in this way can become a routine procedure requiring only the occasional query with the production department. The categories into which breaks are divided must be carefully considered, understandable, and tailored to conditions in each mill and even to individual machines. Obvious examples of the sort of categories normally chosen are:

mechanical (all faults caused by circumstances under the jurisdiction of the engineers—belts, pumps, bearings, guides, etc.)

electrical (starters, motors, supply, etc.)

instruments (controllers, photo-cells, relay systems, etc.)

wire (all faults directly due to deficiencies in the wire—patching holes, repairing cracks, changing, poor drainage, etc.)

wet felts (similarly for wet felts—made-up, edges, patching, changes, etc.)

dry felts (similarly for dry felts—seams, worn, edges unravelling, etc.)
washing up (time lost cleaning up which is attributable to wet-end
conditions—dirt, pitch, slime, cleaners or screens clogged, etc.)
wet breaks (all otherwise unspecified breaks occurring at couch and
presses—dandy picking, sticking to wire or press rolls, tears, etc.)
dry breaks (similarly for dryers and calenders—wads in cylinders,
creasing, calender stamps, etc.)

In addition breaks occurring at specific points of the machine which are
directly attributable to operation of the equipment concerned can be listed
separately, for example size press, breaker stack, coater, H.V. hood, and
so on. Finally, and inevitably, a category for miscellaneous and accidental
breaks is needed, if only on occasion to avoid lengthy arguments.

The data yielded by this sort of analysis requires periodic examination
and it is useful to prepare reports over periods of three or six months
summarizing such information as the average number of breaks per shift
and the average time lost per week (or per hour if the working week
changes periodically) due to breaks in each of the main categories. This
gives management a clear indication of any changing trends on a machine
and highlights the main reasons for lost production in so far as it has been
caused by downtime on the machine.

6A.2 PERFORMANCE DATA

The analysis of downtime data provides a useful indication of the running
efficiency of the paper machine. But this of course tells only part of the
story because it would be possible for a machine to run with few breaks
yet produce little saleable paper. Other attributes of operation, overall good
production, speed, efficiency, and so on, have to be considered. These more
general indices of performance will now be discussed in detail. Each is
important not only for examining week-to-week variations but for
investigating long-term trends and comparisons with other machines and
also for deriving other data which can be used to examine the profitability
of running in different conditions.

6A.2 1 Production analysis

Once attention is turned to the performance of a paper machine in terms of
production it becomes impossible to ignore the different grades of paper
produced. For a machine turning out nothing but a standard newsprint or
M.G. wrapping, analysis of production can follow the same sort of weekly
procedure suggested for analysis of downtime. But most machines make a
variety of grades which, due to the different demands of processing, have to
be run at a wide range of machine speeds. The reason for this and the
differences in production created by various machine limitations will be
examined in more detail later. For the present it is sufficient to note the
advisability of carrying out a production analysis separately for each
major grade of paper produced. Normally grades where machine conditions
are essentially similar can be lumped together, for example where the
differences involve such minor attributes as colour, calendering degree,
and, within reasonably wide limits, loading content. Different substances of

the same grade can be kept together when they cover a fairly narrow range, say over 10 per cent. of the average, but otherwise it is convenient to form separate groups about the most popular substances.

For each individual grade (using this term for convenience to refer to each grouping of grades and substances) the first piece of information required for each making or over a week, whichever is the shorter, is the average running speed of the machine. There is always a speed indicator on a machine and frequently it is adequate for the machineman's booking of this speed to be used. However, because of its importance it is desirable that the correctness of this speed indicator is given a periodic checking, perhaps weekly depending on its reliability, and this is most easily carried out with accuracy by timing with a stop watch a fair number of rotations of an M.G. or drying cylinder the circumference of which has been very accurately taped. Any persistent bias in the indicator reading can then be allowed for. Where speed changes are liable to occur quite frequently during a making it is useful to have a speed recorder. The chart from this can then be used to give more accurately the times of changes and the different speeds run. From this data an average speed is calculated from the individual speeds weighted appropriately according to the time paper was made in each run.

It is quite straightforward, knowing the average speed and the deckle and average substance at the reel-up, to calculate the weight of paper produced. To do this the downtime analysis is used to determine the duration of time paper was actually reeling up. However this procedure is subject to several inaccuracies, in particular due to the fact that the average substance as weighed is only representative of a number of samples. Also if, for example, two widely different speeds had been run for a similar length of time, and practically all the lost time had occurred during the higher, calculation of production in the way suggested would produce a figure greater than the true value because implicit in this calculation is the assumption that time has been lost in proportion to the length of run. This error can only be overcome by analysing lost time separately at each speed, which complicates the calculation somewhat.

For these reasons it is important actually to weigh the paper produced on each reel. This is sometimes carried out on the lifting crane, which is not very accurate. A preferable though not so convenient procedure is to use a standard scales set in the floor. It is important to note in this context that when a downtime analysis is used to characterize machine performance, then this accounts only for paper that did not appear at the reel-up. Thus for complete accountability, all paper that has been reeled-up must be weighed, i.e. weighing must be done before any is stripped off.

The gross production figure for each making, determined either by calculation or by weighing, represents all paper actually reeled up, be it of sound quality or otherwise. Accounting for the portion that proves unsaleable or is spoiled in further processing is important in itself (see below). But for the purpose of assessing performance of the system as a whole and for such essential tasks as estimating future sales potential, the figure of greatest importance is the actual saleable production. This, divided by the

appropriate number of hours actually occupied by the making (normally including preparation time), produces a figure of so many lb. or tons saleable production per hour which is the most direct measure of how well the whole process has operated.

Where all the paper produced is despatched in reel form, large differences in trim waste at the winder (a feature out of the hands of machine crews) can have a substantial effect on this saleable production figure. Accordingly for the purpose of long-term and inter-mill comparison of machine as opposed to process performance, allowances for this are sometimes made by determining the lb. production per hour per inch width of saleable deckle, a measure of production advocated in the U.S. Newsprint Service Bureau's Manual of Instructions.

6A.2 2 Accounting for broke losses

The term 'broke' embraces waste paper in a wide variety of situations. 'Wet broke' is used to refer to the web doctored off presses, 'dry broke' to paper either removed at a break in the cylinders and calenders or stripped off the machine roll. In individual mills reference will be made to 'coated broke', 'sized broke', 'salle broke' and so on according to the origin. In the present context the term 'broke' is used to cover *only* paper removed or wasted between the paper machine reel-up and despatch of the saleable product, i.e. after the machine roll has been weighed for subsequent determination of the gross production. Thus, broke pulled off at the calenders is not included, but broke stripped off the machine roll is. The reason for making this distinction is quite simply that broke at the calenders is made during downtime, and so would be covered in the system of accounting advocated here. Paper stripped off the machine roll, on the other hand, is included in the gross production figure. If this distinction is not carefully followed then there is a strong likelihood that some broke originating at the dry-end of the machine would in effect be accounted for twice.

This definition of 'broke' is the most useful when comparing the overall performance of different machines. The survey conducted by the British Paper and Board Industry Research Association has shown how the percentage of broke to gross production varies enormously from one mill to another (13). Out of some 57 mills, 10 reported a loss of under 5 per cent., but 12 had losses greater than 20 per cent. This variation is of course a reflection of the degree of converting required by different grades of paper, but even so comparisons of similar grades showed considerable variation between mills: coarser grades from 2 to 8 per cent.; fine papers from 5 to 15 per cent. for a low finish, 15 to 25 per cent. for a high finish; coated papers from 15 to 35 per cent. To encourage reduction of these figures the Association has set up a Broke League in which monthly comparisons between mills (suitably coded) are published.

Before broke can be reduced in a systematic manner it must be possible to identify where it is coming from and the reasons it is caused. It is surprising in how many mills it is customary to collect together broke from all sources, taking care only to separate it into grades and colours, and

dump this straight back into the preparation plant or into storage with little or no attention to the quantity involved. This is particularly the case where broke can be added back in large quantities without adversely affecting drainage characteristics on the machine wire or strength of the finished sheet. Until all broke is carefully separated and individually weighed or the quantity calculated it is unlikely that any effort to reduce it will yield anything but a temporary improvement.

The first necessity is to determine gross production of the machine. When a machine is equipped with a pulper under the calenders there is no problem in keeping separate broke which is made before the reel-up. Otherwise some care has to be exercised to prevent it being included with broke stripped off the machine roll. This is, however, not likely to be too troublesome when it is accepted practice for the full machine roll to be removed and weighed before any is stripped off. Some reel changes on slow machines necessitate pulling out the web beyond the reel-up spindle before breaking and wrapping it round to start a new roll; the paper pulled out in this way will not be shown as a break on the usual type of recorder and so, strictly speaking, should be included in weighing of the machine roll.

An alternative system that has been proposed to eliminate the need for weighing of rolls relies for its basis on yardage measurements. Thus, the length of paper passing on to the machine roll is compared with the length coming off the winder or at any separate process such as the coater or supercalender. This could be advantageous where there are difficulties in separate weighing, and it also overcomes the problem of accounting for increased substance in coating, sizing, or impregnating. An additional feature is to measure the equivalent yardage produced at the couch or presses (using vacuum switches to detect presence of the web); this can provide an alternative indication of production losses in the dryers to that which can be derived from working on a time basis, as discussed in the previous section.

Whichever method is used, care in determining gross production off the machine is important because subsequent broke losses have to be compared to it. Defining the centres at which each broke loss is to be accounted by separate weighing and booking is the next task. This must depend on practicability in relation to mill conditions and on the degree of finishing and converting which is carried out. To begin with, there is no point in accumulating a detailed balance sheet accounting for every piece of broke unless this is presented in a form which ensures that improvement is continually sought and persistent offenders are identified. Nonetheless it would seem essential for efficient working that each main finishing operation is treated separately and in each the main causes of broke are identified by the operators concerned. Weekly examination of the data derived from this should be made by both production and finishing house managers. For long-term records, graphs for each main grade expressing the losses at different centres as a percentage of gross production are very useful.

The first point in most systems at which broke must be carefully checked is a winder when this is used. All paper stripped off the top of machine rolls

and removed from within the roll for various reasons (holes, creases, damp patches, dirt spots, substance changing from one order to the next, shade, etc.) should be separately weighed. Most faults at this point are attributable to the paper machine and so careful accounting is important because the losses can be compared to gross production to ensure that increases in the latter are not brought about uneconomically at the expense of lower quality. On fast machines making paper mainly for despatch in reel form, it is customary for whole reels cut on the winder to be sent for re-winding if their quality is suspect or if too many sections have to be cut out of the reel in the time available. A proportion of these reels will be recovered for eventual sale and this must be subsequently credited in the winder broke return. The same applies to reels with quality deficiencies which are held over for closer examination pending a management decision. Reels re-classified to a lower grade due to poor quality, incorrect substance, and so on are likewise credited, though if this is a frequent occurrence it is wise to keep a separate record of the tonnage involved so that a proper assessment of the monetary loss incurred can be made.

A separate aspect of winder operation which is particularly important with fixed-deckle operation is trim removal. This depends entirely on balancing order requirements and the efficiency of the order department in reducing loss to a minimum. As such it requires separate checking and for convenience it is usual simply to compare the deckle used off the winder with the deckle available on the machine roll (which even on fixed-deckle machines must be checked from time to time due to changes in cross-machine shrinkage). A straight calculation based on gross production then determines the maximum tonnage going forward from the winder. With this procedure trim must be kept separate from paper removed for other reasons which has to be weighed; normally this is no problem for trim is usually removed manually, or blown by fan, to separate barrows or direct to a pulper. With variable-deckle machines it is customary to keep dry trim to a minimum by adjusting the width of trim cut off at the wire to suit the deckle needed on the machine roll. This obviously affects the gross tonnage the machine is capable of producing and should be taken into account when considering machine utilization (see next section) but otherwise is a convenient facility for reducing the handling and processing costs incurred with dry broke. Often with variable-deckle operation a fixed allowance is made for dry trim though it is wise to check this occasionally or over a period it will come to be exceeded.

Other obvious points requiring separate broke accounting are reel finishing operations such as supercalendering, coating, sizing or laminating, and particularly salle operations such as cutting, sorting and counting, guillotining, embossing, and so on which can account for quite the majority of the total broke. In each case the major faults causing broke should be individually listed to provide maximum information. Where substance changes, as in coating and sizing, account must be taken of this in the broke analysis. Paper sold as seconds or retree should be separately accounted for as over a long period the percentage in relation to paper passing through the salle gives an interesting basis for checking on changing

standards. Conditioning operations produce an apparent substance increase from moisture absorption and this can be shown as broke recovery. Even without conditioning the process of cutting and sorting will allow some moisture pick-up but normally this would be small enough not to affect the broke balance to any noticeable extent.

It does not require a great deal of organization to ensure that there is adequate weighing and booking of broke at each important point of the system. Each week a balance sheet can be drawn up showing gross production of each grade off the machine, and subsequent losses at each of the broke centres. It is unlikely that broke will be weighed at all centres so some will be determined by subtraction from the others, but when broke is individually weighed at all points the discrepancy between the total and the difference between gross and saleable production provides a useful guide to accuracy. Detailed information of the individual causes can also be included. When a winder is used with a fixed-deckle machine the loss at each centre subsequent to this can be expressed as a straight percentage of gross production less trim loss since this represents the paper going forward for finishing. But generally it is simplest particularly with variable-deckle operation to express broke at each centre as a percentage of gross production off the machine. Over a period, an upper limit for broke at each centre can be set, and whenever the quantity exceeds this limit this can be regarded as showing the need for closer enquiry.

6A.2 3 Efficiency measurements

The information made available by the various indices of production and analysis of broke losses provides all the basic statistics needed to ensure that operation of both the machine and finishing processes are adequately monitored. But it is often useful to have a concise figure which gives a quick and simple indication of overall performance. For this purpose various 'efficiency' figures can be determined (1, 6, 9, 14) and those which in the opinion of the author are most useful will now be discussed.

Unfortunately there is no standardized procedure for calculating efficiency. Methods vary from one mill to another, and reference to 'machine efficiencies' is generally unhelpful when commenting on the effect of some operational change. A sub-committee of the TAPPI Fourdrinier Committee has examined the problem of deriving an efficiency figure that will allow inter-mill comparison. They decided that the simplest definition for universal use is

Paper machine production time ratio =
Actual running time × 100/Scheduled running time

This definition is appropriate for 7-day operation and for a working week of fewer hours conversion factors are suggested which allow for the different conditions. 'Actual running time' covers the time when paper was being made on the reel reduced *pro rata* according to the percentage of subsequent broke. 'Scheduled running time' is all the time for which orders are available to run the machine and with delays for any reason including order changing but making a reasonable start-up allowance. This definition of efficiency is as good as any for the purpose of inter-mill comparison

and takes account of losses from all sources. On this basis efficiencies for newsprint machines vary from 85 per cent. to as high as 97 per cent. The Committee considered 80 per cent. the minimum tolerable but it is likely many mills run at 60 per cent. or lower efficiency.

The above definition is equivalent to

$$\frac{\text{time paper at reel-up}}{\text{total time available}} \times \frac{\text{saleable production}}{\text{gross production}} \times 100$$

where the terms 'saleable' and 'gross' production are respectively the weight of paper actually sold and the weight of paper produced at the reel-up. This efficiency figure is therefore readily calculated from the analyses of downtime and production already described.

Using the time paper is at the reel-up compared to the scheduled time available is a direct and simple method of measuring efficiency of the machine itself. A similar figure can be derived to give a measure of efficiency of just the wet-end of the machine by taking the time the web passes over the couch. But efficiencies calculated this way represent only one aspect of operation. They take no account of speed and it is well known that running a machine faster causes on average a greater number of breaks. If no account is taken of speed it will be found that a machine appears to have a higher efficiency the slower it runs, and in any absolute sense this is patently ridiculous, even though in some circumstances a greater production may be turned out at a lower speed due to a higher proportional reduction in lost time. Hence use on its own of this definition of 'efficiency' will be misleading, and a mill attempting to tie bonus agreements to such a definition will be jeopardizing its future.

It is preferable to use the term 'machine time efficiency' to cover the percentage of time paper is at the reel-up in relation to scheduled time available. For internal use, however, a definition is needed which applies only to the paper machine and yet takes account of speed and substance variations, one in fact which assesses as truly as possible the actual weight of paper produced at the reel-up compared to what could have been produced in ideal circumstances. The difficulty lies in deciding what 'ideal' circumstances are since this implies deciding a maximum runnable speed for each substance. In practice it does not really matter at all what value is taken as an upper speed limit, provided once fixed it is kept at the same figure. Calculated efficiencies will be higher or lower depending on how low or high is the chosen maximum speed, but this is immaterial so long as they are directly comparable. Many mills in fact prefer to use a reasonable average speed actually run in the past as a basis for calculating maximum production; this is prefectly all right so long as it is rarely altered and, of course, so long as efficiencies are always under 100 per cent. For machines running a single grade with a low substance range, a single production figure based on some maximum speed, substance and deckle can be used for direct comparison with gross production off the machine. But on most machines if the efficiency figures are to be at all comparable some realistic maximum speed must be decided for each grade and substance range. Methods of doing this are discussed in detail later.

The efficiency figure produced in this way can be termed the 'machine production efficiency', and this will therefore represent a percentage comparison of actual gross production at the reel-up with what could have been produced in the scheduled time available at some agreed maximum speed for each substance. Taking this a stage further, 'overall production efficiency' becomes the net saleable production related to the same denominator. As a final refinement the net saleable production can be expressed as a percentage of the paper that could have been produced at maximum speed for each substance in the complete working week, including shuts for maintenance and normal starting-up allowance. This may be termed 'plant efficiency'.

These various definitions are summarized in descending order of magnitude as follows:

Wet-end time efficiency =
time web at couch × 100/scheduled time available

Machine time efficiency =
time paper at reel-up × 100/scheduled time available

Machine production efficiency =
gross paper at reel-up × 100/maximum possible paper

Overall production efficiency =
saleable paper produced × 100/maximum possible paper

Plant production efficiency = saleable paper produced ×
100/maximum possible in complete working week

where 'scheduled time available' is the operating time including grade changes, a minimum start-up allowance, and all sources of downtime; 'maximum possible paper' is the weight of paper that could be produced were each grade and substance run at maximum speed and deckle for the time actually occupied by the making; and 'full working week' includes time allowed for start-up and maintenance.

These definitions of efficiency cover the machine system as a whole, but the efficiencies of individual parts of the system are probably more conveniently expressed in terms of their own maxima. Thus the significance of 'trim efficiency' is best appreciated if it is defined as:

trim efficiency = actual deckle average ×
100/maximum deckle available

where 'actual deckle average' represents the average of actual deckles produced at the machine roll or winder weighted according to the tonnage produced at each deckle. Similarly, for a coater, efficiencies might be defined as:

coater time efficiency = time paper at coater reel-up ×
100/scheduled time available

coater production efficiency = gross coated paper at reel-up ×
100/maximum possible coated paper

where 'maximum possible coated paper' is the weight of base paper used increased *pro rata* according to the coating weight added.

The main point is that each definition should be readily understood, considered fair by the operatives, and available to assist supervisors and management to make an early detection of deteriorating conditions or tell when there has been an improvement. As with the other indices of performance, a weekly graph with arbitrary upper limits to guide when remedial action is desirable should be plotted for each efficiency figure. For long-term appraisal an average covering three to six monthly periods should be circulated to all relevant departments and comment made on any trends.

There remains one final aspect of efficiency which is of a rather different nature, that referring to the usage of raw materials in relation to the output of paper. When for one reason or another broke cannot be re-used (fluorescent dyes, unsuitable colour, parchment, etc.) it may have to be sold at a scrap price or even dumped or burnt. Obviously it is then desirable to keep a separate account of this as it represents a direct loss to the mill and reduces the efficiency of raw material usage. Fortunately as it is common for all broke to be used in one way or another, so all fibre and loading fed in to the system in the preparation plant leaves as saleable paper apart from the proportion that is drained to waste in the backwater system and elsewhere. The more closed the backwater system and fewer the grades necessitating prior wash-up involving draining the wet-end and the remains of chests, the less will be the loss of fibre and loading.

Derivation of this 'furnish usage efficiency' can be performed in two ways, neither very satisfactory. The first involves a straightforward comparison of the weight of pulp and loading fed in with the weight of paper sold. Although this obviously fluctuates from week to week as more or less broke remains in storage or in the system for processing, over a fair period the average should give a reasonable measure of furnish usage efficiency. Note, incidentally, that weight of broke used in any particular furnish is irrelevant to this calculation. The main source of inaccuracy is that normally the weight of bales and their moisture content is known only from a sample average, and similar problems apply to loading batches. Also some allowance must be made for moisture present in the finished paper, yet this fluctuates especially when sold unconditioned.

Such a calculation is not feasible anyway when a mill produces its own pulp, unless this is dried and stored before use in which case it is possible to add up the various beater charges and allow for moisture content from sample determinations. An alternative method is to make a direct determination of the fibre and loading passing to drain. This has been discussed in TAPPI Information Sheet No. 598.01. Provided all waste is channelled to a single drain it is quite possible to sample from this manually at periodic intervals or to use an automatic sampling device which every few minutes draws a small volume into a storage jar. Subsequent analysis of the mixture of samples yields an average value for the consistency and loading content of the drain water, and this together with a flow average gives a tolerable estimate of losses (3). This can then be compared to the saleable paper produced and expressed as a furnish usage efficiency.

6A.3 MONITORING QUALITY

The first concern of the papermaker is to secure maximum output from his machines. Following a close second is the need to maintain quality of the paper produced. In many cases production and quality are very closely linked, for improvement of the one is difficult to secure without deterioration of the other. The whole subject of quality has in fact become far more important than ever before, and now demands a considerable proportion of the papermaker's time. Various general aspects of this will now be discussed.

6A.3 1 The scope of quality control

The need to apply some sort of standard to the grades of paper produced on a machine has been evident for a long time, and from early days it has been customary to extract samples from the end and occasionally from the middle of machine rolls in order to check that substance is close to what is required. It has also been traditional to issue to the machine crew a sample either of the previous making or of sheets laid down as standard for the grade concerned, and expect this to be matched as closely as possible. The rising quality demanded by customers and increasingly competitive nature of the paper trade has exposed the inadequacies of this simple system so that nowadays it is general practice to apply a more detailed examination of paper at the reel-up.

The main object of this examination is to indicate when quality is not up to the standard required so that action can be taken by the machine crews to correct this. The term 'quality control' has come into general use in the industry to describe this operation, though a more accurate term would be 'process control'. The distinction is a fine one, because 'process control' implies that the purpose is solely to indicate the need for action in order to reduce variation to a minimum and keep as closely as possible to the standard required. 'Quality control' on the other hand implies that some sort of inspection and rejection of the product takes place before it is passed to the customer. This does not happen when straightforward 'process control' is applied, though naturally it contributes to that end. To distinguish more carefully requires using the term 'process control' to cover end-of-reel sampling and testing, while the term 'product control' is often used to denote an inspection and rejection procedure. In deference to general usage, however, it is proposed to label these functions respectively 'quality control on the machine' and 'rejection scheme'.

Although initial emphasis has been on the need to apply quality control on the machine, and this indeed is the main topic of the present section, there is increasing realization that this alone is insufficient to ensure an adequate product. There must also be a general application of quality control throughout the mill, particularly to incoming raw materials. Pulp, loadings and chemicals should all be subjected to routine testing against a specification. Also quality control needs to be applied in all areas of the mill where variation can affect the final product, though generally the application of instrumentation and conventional process controllers are taking over this role. Most important of all, the status and organization of

the department responsible for quality control must be such that it is regarded as making an essential contribution; not an unproductive liability but an integral part of the papermaking process.

It is not proposed to discuss these points further, but to turn now to what must be considered the key to successful monitoring of quality, the scheme for checking at the end of the machine. The mechanics of this will be discussed later, for the moment attention is turned to the fundamental question: what aspects of quality should be brought into the scheme?

In the first flush of enthusiasm for quality control it was not uncommon to find literally dozens of tests being applied to samples drawn from the end of machine rolls. Each grade would have standards applied for as many tests as it was physically possible to accomplish in a reasonable time, and wherever possible limits would be applied within which the machine crew was expected to keep. Occasionally a customer might make a complaint about some specific property, so the matter would be dealt with by introducing a further test. After a few makings had established a typical level for results of this test, it would join the others with limits set, for good measure, well towards the high side.

This sort of procedure commended itself to management because it seemed that here was an excellent means of keeping up quality levels. Unfortunately it soon became apparent that nothing of the sort happened. The papermaker would find not only that he was supposed to watch too many qualities but that frequently altering one to bring it within limits would cause another to go out of limits. Some properties would appear to set themselves at a particular level at the start of a making and no conceivable alteration to operating conditions would yield an improvement. In time nobody would take any notice of half the tests performed, and the inevitable acceptance of this by management would affect the attitude of the machine operatives and jeopardize the value of the remaining tests.

The basic error in all this was lack of realization on the part of the enthusiasts introducing quality control of just how empirical the process of papermaking still is. There was, whether consciously or not, the expectation that the average operative possesses the wisdom of knowing precisely which action influences what, combined with the speed of a computer to determine how much alteration to each variable is needed to achieve the best compromise. In practice it is useless to apply quality control to any property unless a definite corrective action within the power of the machine crews is available. When control of some property is vital and an obvious corrective action is not known, then research and experimentation on the machine is needed to fill the gap in knowledge. Likewise, when a particular corrective action influences more than one property, the extent of the interaction should be tabulated for the operative's guidance. When two or more properties are obviously closely linked, only one of them should in any case be subjected to quality control.

Unless these simple points are followed the machine crews will inevitably find they have an impossible task on their hands. One or more specific properties will be impossible to control or raise to the required standard and after repeated attempts this becomes accepted, with the danger that in

time really vital properties come to be regarded in the same way. Quality control is likely to be successful only when it is possible to demand and receive a valid reason for a property being persistently outside the levels laid down, and then to devise a means of preventing a recurrence.

Properties that fall into this category are mainly the basic ones control of which is fairly straightforward. These include: substance, moisture content, thickness, smoothness, loading content and the simpler strength properties such as burst and standard average tensile. Certain other properties are also readily controlled depending on the type of paper being made and include: porosity, colour and brightness, gloss (of coated papers), wet strength, crush resistance, and water penetration for sizing. In each of these cases there are more or less standard testing instruments available which have to conform to a detailed specification. Equally important, a controlled corrective action to the paper machine or the preparation system can readily be made to alter the test value of the paper produced to a new level.

Properties that should be avoided for quality control purposes include those for which test methods are vague or their significance doubtful, and those which are basically traditional and assess attributes of paper that are difficult or impossible to measure. Above all, properties that relate in some dubious way to the end-use of the paper and for which ingenious tests have been devised should never be applied to quality control; if in some misguided moment the apparatus concerned has been purchased as a gesture of co-operation with the customer, then it should not leave the hands of the mill laboratory. Examples of the properties which fall into these categories include: folding endurance, softness, handle, twist-resistance, water-vapour permeability, water absorption, abrasion resistance, and hygro-expansivity. Each has its place in an investigation, but if the test concerned is all-important to the end-use of the paper then either the relation between it and some of the earlier tests mentioned should be determined, or some ready means of correcting the level of the property by altering operating conditions on the paper machine must be devised. There remains other tests, tear, printability, curl, opacity, formation, and so on that fall somewhere in between the two extremes, and the position with regard to these must be considered somewhat open at the present time.

6A.3 2 Applying quality control

Once the properties to come under quality control on paper machine rolls have been decided, there are a number of further important aspects to consider. Broadly speaking these cover the mechanics of the quality control scheme and involve such questions as how and in what manner samples of paper are to be obtained, how these are to be tested, what limits are to be placed on the results, and what action is the machine crew then expected to take? These are subjects that have received a great deal of attention in numerous articles and one or two books and will be discussed here only briefly.

The manner in which a sample of paper is obtained from the top of a machine roll must be related to the type of properties to be tested in the

quality control laboratory and the number of individual test operations required for each property. For each property a compromise must be reached in the number of individual test results to be performed which best satisfies the need for accuracy of the average with the time available for carrying out the operations. The value of quality test results diminishes with the length of time they need to execute and normally this issue settles how many individual tests are made. It is, for example, a simple matter to make several thickness and substance tests but each separate measurement of tensile strength, ash content, and folding endurance is time consuming. A systematic approach is possible and has been outlined in the British Paper and Board Makers' Association Technical Section Proposed Procedure No. 47: Guide to Sampling from Rolls for Quality Control. This discusses the requirements of sampling and the practical problems involved, and also illustrates with examples how the number of individual test readings for properties with different variability can be decided. The influence of cross-machine variability on the sampling procedure is also discussed.

Once a testing procedure has been in operation for some time, average results for a succession of machine rolls become available and the question of setting limits on either side of the desired mean value arises. The purpose of these limits is to give a guide to the machine crew when action is needed to prevent the property in question straying too far from the required mean, and this then has the effect of keeping variation in that property to a minimum. For this task the actual value of the limits is not of crucial importance so long as they assist in defining a set course of action for the operatives to follow. Numerous ways of determining suitable limits have been devised (see, for example, reference 2), and many sophisticated systems are available. But for papermaking it appears unnecessary and undesirable to attempt anything too elaborate.

Probably the most straightforward method is in the first instance to set limits for each property on the basis of the average variation that has occurred in the past during a number of separate makings. This will include all the variations inherent in the system (which by definition it is not within the power of the machine crew to reduce), plus variations deliberately introduced in the course of making alterations to the machine for one reason or another. Ideally the latter should be discounted, but except where a gross change of level in the figures is obvious this is not possible. Statistical analysis of the results of past makings will permit calculation of the average variation in the form of the standard deviation, σ. Limits imposed are usually plus and minus 2 σ and it is then intended that these serve as a warning (when the property value falls outside the limits) that something may have upset the level of the property and a correction is needed. Further limits of plus and minus 3 σ are also sometimes used to indicate when corrective action is absolutely essential. Machine crews are usually advised not to touch the process when test readings fall within the 2 σ limits, though in practice trends from previous results are sometimes discernible and an alteration may be made earlier.

In the case of some properties the only requirement will be for either an

573

upper or a lower limit, not for both. It is then necessary to decide whether to use the appropriate single limit or nonetheless impose upper and lower limits. This decision depends mainly on the importance of the property. If it is largely irrelevant except to meet a specification, then a single limit can be used. But if there is the likelihood of incurring higher making costs by permitting the property concerned to move too far in value away from the mean, then obviously double limits are needed. The best example of this is in the matter of strength, where the end use will often require only a minimum value, but a maximum limit is also needed so that furnish or power costs are kept to the minimum necessary.

Once corrective action for some property is clearly required, the operative has to decide how much alteration to make to the appropriate machine variable. This procedure is commonly a haphazard one in which an operative adjusts a valve or alters the position of an indicator by an amount that he adjudges necessary. He will invariably aim at re-setting the property value exactly to the required standard, i.e. in the middle of the limits, but if he is at all over-enthusiastic the degree of correction applied will be too great and the test result off the following roll will show that a counter-correction is needed. Avoidance of hunting in this way is very important, and one method that has been advocated on theoretical grounds is to provide two target values to aim at when making a correction. One of these values would lie above the required mean and is intended for when a result has appeared above the upper limit, and the other below the mean for when a result is under the lower limit (11). Whenever possible, however, there should be some guidance provided on valves and indicators to show how much movement produces a given change in property value. This, unfortunately, is rarely possible unless a detailed log is kept of all alterations made on a machine, though with the advent of closed-loop on-line computer control this type of operation will become at one jump completely automatic.

6A.3 3 Setting quality standards

The care needed in selection of which tests are used for quality control has already been mentioned. Equally important is the value of each property chosen to be the standard for a particular grade. In certain cases this is clearly settled by trade agreement or British Standard requirements, for example the substance of many grades, the loading content of printing papers, electrical insulation of condenser paper, and so on. Several other properties will, from custom, require to be kept at certain values, but with many there will be a tendency when first deciding on a standard to examine the scatter of averages for past makings and select a value on the high side. This is done in the belief that a higher burst, finish, thickness, or what have you is synonymous with higher quality. In some cases this may be so, but not in all, and before a high level is agreed on other aspects must be considered. For example, if a higher strength than the former average is chosen, is this going to lead to higher making costs? Also, would a lower strength not be sufficient for the customer's needs anyway, or have there been complaints in the past of low strength? A further point regarding

standards is that there is never any virtue in requiring, for the sake of argument, a particular porosity level for a fine writing when this is both irrelevant to the end use and of no particular significance in determining the basic characteristics of the paper.

When a customer suddenly starts requiring a definite standard for certain properties the matter can become rather complex. In the first place he is almost certainly going to ask for a tighter specification than he needs. And what he needs will invariably be based on what he has received previously. So the manufacturer is faced with having to make to a standard which equals or exceeds the best he has achieved in the past. In some cases this could well necessitate greater making costs to reach consistently the levels required. When this is the case, obviously careful negotiation is necessary and a polite but firm enquiry into the real needs of the customer has to be made.

Particularly invidious is the situation where the customer demands that the degree of variation in the test results of a particular property is reduced to a lower level than hitherto. It is no use the manufacturer simply reducing the width of quality control limits applicable to the property concerned, because it is not within the operative's power to reduce this variation at will. Faced with the imposition of narrower limits, there may well be an initial improvement until the operatives come to feel they face an impossible task as readings out of limits appear with monotonous regularity. In time the application of this particular control will fall into abuse and the limits become meaningless. Whenever making conditions are known to have a natural variation which is too wide to meet a customer's specification, then either the papermaking process has to be modified in some way to permit the specification to be achieved, or the specification limits must be widened to a more realistic value. It is often the case, however, that tight specifications can be met provided a lower machine speed is run. As this almost certainly implies lower production, it is important that management is made aware of the necessity and agrees to the situation.

Brauns (16) has presented some interesting reflections on the whole question of quality levels for competitive grades of paper. He draws attention to the arbitrariness with which it is first decided to test certain properties, and how a level is agreed for these properties which depends mainly on what can be achieved in relation to competitors and which can often be largely irrelevant to the end-use requirements. As a result of the establishment of particular levels for various properties, the quality from different manufacturers will gradually become similar, but whether this is in fact the best compromise between the manufacturing cost and the genuine needs a customer has it is impossible to tell. Eventually one manufacturer will cut the level of a property and reduce his price. The new level will be found by the customer to make no obvious difference, so he will demand a similar cut in price from competitors who may take some time to discover that the necessary economy can be achieved by lowering quality standards.

Inevitably the needs of the customer must influence quality standards, and quite rightly so. For this reason a careful record of complaints by

customers should form an integral part of a quality control department. To aid tabulation, the use of a standard form for representatives to fill in is useful, though a tendency to draw attention to complaints simply because they are listed as possibilities must be avoided. It is preferable that a complaint originates specifically from a customer than that he is questioned as to whether he has experienced difficulty from this or that. Some complaints will always be made, and the manufacturer who has conscientiously made paper to an agreed specification will nevertheless find the customer producing trivial complaints of damage or of some difficulty in use which may often be due to the customer's own negligence anyway. Such circumstances then become more a question of business relations than a serious technical matter.

6A.3 4 Organization of quality control

Successful operation of quality control depends much more on efficient organization and documentation than on the precise calculation and frequent revision of limits. The whole procedure of sampling, testing, and recording must be rigidly defined, and the action required in the event of different circumstances occurring has to be clearly laid down. It is not intended to deal with this aspect of quality control in any detail as there are many excellent articles (see, for example, reference 18), which discuss the merits of different organizational structures for quality control and give examples of the sort of forms that can be used for standard cards, recording test results, summary sheets, control charts, etc. Discussion will be confined to a few of the more important points that in the opinion of the author need careful attention.

Perhaps the most important single assurance that a quality control scheme works well is that a sound attitude to it is adopted by management and production supervisors. Continual vigilance is needed and whenever quality falls an immediate enquiry should automatically follow. Many mills have daily meetings during which quality deficiencies occurring over the previous twenty-four hours are discussed and decisions taken regarding rejected batches. Above all it is essential that the machine crews whose job it is to operate the quality control scheme are made aware of the seriousness with which bad and persistent infringements of the limits are regarded. This is not to say that in this event an operative must be blamed for slackness, but that a genuine enquiry is made into the reasons for low quality and when this is no fault of the operator (as is frequently the case) a willingness is shown to get to the bottom of the matter and prevent a recurrence. On such occasions careful questioning of machine crews often brings to light surprising explanations for poor quality and closer investigation shows up the need for some alteration to equipment or operating procedure.

The manner of presentation of quality control results to machine crews is important and it is generally agreed that some form of simple graphical method is preferable. Graphs on paper can be kept for record purposes in the quality control laboratory, and one or other of the patented systems of presentation on magnetic or pegboards used in the mill. For each property

the limits must be clearly shown, together with the last few results. Usually some means of drawing attention to the results for properties which look to be going out of control is also incorporated. Speed of operation is essential and it is useful to method study the whole procedure of testing to devise the best routine and lay out for the laboratory; whenever practicable rapid methods of testing should be used, leaving more rigorous techniques to be carried out on humidified samples for standardizing purposes. Transmission of results from the laboratory to the machine must be by some quick and accurate method, and in some mills it has been found useful to use close-circuit television for this purpose.

It is especially important that the quality control laboratory is, and is seen to be, a model of efficiency. The machine crews must be able to rely implicitly on the accuracy of the results presented to them and there should never be suspicion that they may be in error. Once crews begin to question the validity of any results, the whole climate of working is liable to change for the worse. It is advantageous to rotate the shifts of the laboratory testers in the opposite direction to those of the machine crews. To ensure accuracy of test results it is essential that all instruments used in the laboratory are subjected to frequent comprehensive checks following the standard methods laid down by national organizations and in some cases by the International Standards Organization. Any instrument suspected of bias must be immediately replaced or taken temporarily out of use. A record of repairs and alterations to each instrument is worthwhile keeping.

To reduce operator error a good standard of training is required and detailed operating procedures for each test should be drawn up. The importance must be stressed of recording only results that are actually determined, and never results that at the time may seem more realistic or likely; the value of honesty in this matter cannot be too lightly dismissed for it is inevitable that pressures are brought to bear on testing operatives to produce figures that do not show too wide a deviation from those required. At the same time the possibility of error in the laboratory can never be discounted and it is useful to have a recognized procedure for re-testing and, if necessary, re-sampling whenever a single test result or an average is very different from previous values. For individual test results a number of statistically valid techniques giving an objective criterion for rejection of the result are available, and one or other of these should be adopted in preference to leaving such a decision to the discretion of the tester.

The results accumulated by the quality control laboratory are useful not only for their immediate purpose on the paper machine but for providing longer-term information on quality. For each making, or over a period of a week, it is a simple matter to determine the average value attained by each of the properties tested. Some laboratories also determine the standard deviation but this involves considerable calculation which, for the additional information provided, is of doubtful value unless the process is performed by a computer. A simpler method giving a ready indication of the degree of variation within a long making is to determine the percentage of results which appeared outside 2 σ upper and lower limits. Graphs of the

average weekly quality levels are useful for indicating trends, and when a number of machines making similar grades from the same furnish are involved such graphs can on occasion serve to eliminate possible reasons for a drop in some property because the same trends are discernible on different machines. Errors due to sudden bias in an instrument can also be occasionally detected. At three or six monthly intervals overall property averages for certain common qualities provide useful information to present alongside downtime and production data. Occasionally all standards should be reviewed with regard to the average level and the limits imposed and alterations made to bring them into line with recent performance.

These are a few of the more important considerations that make for good quality control practice. They should help to ensure that the cost of running a laboratory is amply paid for and that the paper leaving a mill has as good and uniform a quality as can be economically provided. In time it is to be expected that most aspects of quality control will gradually be replaced by the use of continuous testing instruments at the end of the machine roll, but in many instances it may well be found that the cost of investing in sophisticated equipment of this type together with the qualified supervision needed for it would be higher than the savings in manual work involved in the usual form of testing.

6A.3 5 Rejection procedure

It is valuable for the machine crews, particularly the dryermen, to feel that the work of the quality control laboratory is genuinely helping them in their own task. A simple means of encouraging the right attitude is to involve the dryerman in the quality control operation. This is necessary in only a small way, as for example if the dryerman is given the job of signalling to the laboratory a short time before a roll is ready or is made responsible for marking the results up on a chart or board. In some mills the dryerman is also made responsible for drawing the sample for testing and provided this is performed in a carefully defined manner from the top of the roll it is unlikely to be abused. Many mills, indeed, like to encourage dryermen to do as much as possible of the testing themselves, arguing that it should be within their sphere of responsibility for producing a satisfactory product. This procedure does not, however, find very general acceptance partly because it tends to load more work on to the dryerman than seems justifiable, but mainly because of a suspicion that the job would not be fairly performed. Nevertheless in some circumstances, and especially when there is independent and subsequent inspection testing, it can be an acceptable procedure.

The most useful incentive to comply closely with quality control results occurs when they are associated with some sort of rejection scheme. In this case the test results are used not just in an endeavour to minimize variation and keep quality closer to the required standard, but also as part of an inspection procedure. In other words product control is incorporated and the whole system becomes a quality control in fact as well as name. Frequently, as in the case where sales are in reel form, there will be no

further testing after the end of the machine to check for matching to a specification, and so a rejection procedure associated with the conventional form of quality control becomes essential.

Rejection limits used on tests taken at the end of the machine are frequently fixed at plus and minus three standard deviations from the mean. When a tight specification has to be met, narrower limits can be necessary but this is an undesirable state of affairs which could involve excessive waste. It is probably of some benefit to incorporate rejection limits on all properties, whether or not the paper concerned is liable in each case for rejection from being out of specification. The mill is then applying its own inspection standards and not simply having them imposed. With properly determined statistical limits application of rejection limits at this level should not lead to a much greater loss of saleable paper and can be advantageous in securing more reasonable specifications with new customers.

When paper is destined to be immediately slit and cut in the salle, it would be usual to have some sort of inspection procedure operating on all individual sheets or more commonly on a random sample of the sheets. Reels with some property outside a rejection limit are then often simply put to one side pending a decision from management on their future. Further testing may be required to check the original value, and if the property is extremely important there may be no alternative but to strip the reel, but often it will be possible to sell it as retree or seconds, or to reduce it to a lower grade. The appropriate action depends on how comprehensive the sampling testing procedure is in the salle. If there is a well designed scheme incorporating statistically designed acceptance/rejection limits it could well be cheaper to let a low-quality reel pass through the system and hope to recover as much good paper as possible from it.

When rolls off the paper machine pass directly to a finishing operation or to a winder for slitting to size and packing, then a rejection procedure must operate immediately whenever tests from a sample at the top of the roll indicate that a property lies outside the rejection limits. Different methods are in use, but a straightforward approach would be to hold the roll temporarily and sample again for a check. Ideally this should cover all the usual properties tested because when one property is suddenly well out of specification a clue as to the reason for this can sometimes be derived from a comparison of other property values, but usually shortage of time will preclude the checking of any properties other than the one most concerned. If the average of the original test and the check are inside the rejection limit, the roll can then be passed. But if rejection is confirmed, there can be standing instructions requiring immediate stripping of a layer 2 to 3 inches deep followed by further sampling and checking, and so on until a value within the limit is reached. The main trouble with this procedure is the delay it creates in the steady flow of rolls to the next process, but there should normally be sufficient slack in the system to permit this. If a roll has already gone forward there is little that can be done without interrupting the process except eventually to draw a sample from wherever the roll has unwound to, and then await results from there.

When a property is out of rejection limits at the top of a machine roll, it must also be out of limits at the start of the new roll. Hence whenever a property is reported out of rejection limits immediate action is required to make a correction. So long as there is some confirmatory evidence on the machine, correction should be made before a re-check of the property has been obtained. It is now necessary to tear a slab from the machine roll, even if machine speed makes a break inevitable as a result, as soon as it is likely that the property has been brought back within limits. Several samples from within the roll may be necessary before this is finally achieved, and when the roll is later unwound all the paper below where the final sample was drawn usually has to be torn up. A report on the total quantity of paper rejected and the reason for this must, of course, be submitted by the supervisor or machine operative and it is useful to compile a weekly summary of these losses.

Such a rejection procedure may well seem a bit drastic, but in a well-ordered mill with properly determined limits it is not likely to be used very often. If, for instance, plus or minus 3 σ limits are used for rejection, then an average of one roll in a little under 500 would appear to require rejection when in fact this was not the case (checking would then in practically all cases confirm that the roll was alright). This is a small price in wasted effort to pay for guarding against the odd occasion when a genuine and undetected disturbance to the machine does cause a property to stray in value well away from what is required. In any event, not every rejection limit need operate as a true criterion for rejection when it is not part of the specification required by the customer, and if some specific property is persistently beyond a rejection limit the time will have come for a close investigation into the reasons for this and into the value of the limit itself.

CHAPTER 6B

IMPROVING MACHINE PERFORMANCE

6B.1 GENERAL SURVEY

In a production system like papermaking there is inevitably over the years a steady decline in the performance of equipment due to gradual wear and tear. At the same time bad operating habits can gradually creep into the work of machine crews and poor quality, once accepted, can slowly become the norm. Supervisors, with the help of engineering and technical personnel, attempt to arrest this insidious process of deterioriation by training and encouraging operatives to improve their standards and by maintaining equipment well and periodically renewing it. Throughout the mill, supervisors and operatives alike should be on the look out for ways of making improvements and any suggestions should be taken up as a matter of course once they can be shown to have economic merit.

Certain specific aspects of this continual quest for improved performance will be dealt with later. For the moment it is intended in the present section to examine, in the broadest possible sense, the various ways in which losses in production can occur and how these may be overcome. Not every mill will suffer from the same sources of inefficiency, but the basic principles should still apply. Attention is naturally concentrated on the Fourdrinier machine itself, though some consideration is given also to operation in other parts of the paper mill, especially when these impinge on production.

6B.1 1 Improving working procedures

There are a number of situations on a paper machine where an improvement in working procedure can serve usefully to reduce downtime and broke. This applies particularly to start-up, shut down, grade changes, clothing changes, and shuts for routine maintenance.

Starting up a machine is a frequent enough occurrence yet the sequence of operations carried out is likely to vary appreciably from one machine crew to the next. Once it is accepted that a machine requires so many hours to get under way, and that for quite some time afterwards the paper is anyway fit only to be stripped for broke, then inevitably this becomes the normal standard. The very familiarity of the operation makes it difficult for operatives and supervisors to see any fault in their customary procedure, and when something unusual happens (more often than not to the quality of the paper) it often seems on the surface that nothing has been done which is different to the usual method employed, and so there is no obvious explanation.

An efficient start-up depends primarily on two features: proper design of the system and adequate training of the crews. Of these, the first is more important because ideally a system should be so arranged that it is impossible to go seriously wrong when starting it up. For new paper

581

machines the techniques of systems engineering can be brought to bear in such matters as deciding the size of chests and pits, the critical points to apply control, and the precise sequence of operations to minimize disturbances. On existing machines a careful analysis of the customary start-up procedure will often indicate obvious sources of delay. For instance, it might be that the fresh stuff is ready well in advance of when the machine-man can use it due to the length of time needed to heat up drying cylinders or fresh water in the backwater silo. Provision of a separate steam supply line for start-up would then be an obvious remedy.

Closely connected with this aspect of an efficient start-up is the time required to reach equilibrium conditions once stock is on the wire. It is evident that when fresh water is used for the first dilution of fresh stuff, some time will be needed before re-circulation builds up the fines content to a level near that eventually reached. But usually this in itself does not cause any delay because the machineman has many points to inspect before feeding across from the couch and by then equilibrium conditions will have been all but established. Subsequent delays in feeding through presses and dryers can often be due to inadequate preparation (wetting out of press felts, decreasing dryer temperature at an appropriate time to prevent overdrying the web). It is, however, in less obvious attributes of consistency, colour, pH, and so on that troublesome disturbances can arise before equilibrium conditions are achieved; for instance, whitewater circulated through a save-all and returned to the stock preparation system can introduce a variation in these characteristics that needs many hours to reach equilibrium. Often, too, inadequate care is taken to try to ensure that the first batch of fresh stuff is supplied at the correct pH and temperature, or that the water used to dilute it approximates in these respects to what will be used once recirculation is established. All these considerations contribute to the usual situation where it is accepted that feeding through on the first occasion always produces numerous breaks, and when the sheet is finally up the first paper appearing at the reel-up is in any case not up to standard for one reason or another.

The need for adequate training of crews in starting-up procedure is self evident, but this is assisted by providing each operative with a check-list of points to go through at each start-up. This should cover not only routine inspection and cleaning (as outlined earlier in the relevant section on each part of the machine) but also such matters as pre-setting of all machine variables (valve positions, draws, loads, etc.) to suit their normal levels for the particular grade to be run. The duties and area of responsibility of each operative should also be carefully defined whenever ambiguity is possible. Where it is particularly important that a definite sequence of events is followed (to prevent overflow, too high stock consistency, excessive power demand, etc.) it is preferable that mechanical or electrical interlocking devices are incorporated in the appropriate actuating mechanisms.

Much the same points apply also to shut-down and grade changing procedures. In both these cases accurate estimation of the time of completion of an order or a machine roll contributes to reducing wastage at the end. The sequence of operations when changing grades by running

through from one order to the next should be carefully planned to reduce the quantity of paper made in the transition period. This is not difficult to arrange when only a substance change is required (see the discussion on this point in 1C.44), but for a colour change much greater care is needed to prevent a lengthy period of gradual change on the roll before the final match is achieved.

In some cases of colour change it may be economically preferable to shut the machine, drain the system and start up again, even though it would be possible to run through. This is necessary anyway for some colour changes where a thorough wash-up is needed. The procedure for handling this situation should be defined to keep the time involved to a minimum, and particularly when it is a frequent occurrence study of the customary routine could well show up defects in the machine design which causes delays (pits too slow to drain or fill, inadequate hose pressure, etc.).

Scheduled shuts for maintenance come more into the province of the engineering department. It is evident that careful planning of a system of preventive maintenance with staggered examination of different items over a period of weeks will contribute to keeping the time required to a minimum. The production personnel should be adequately informed of work to be carried out on the machine so that they can plan their own jobs to avoid too many men working in one area or requiring at the same time such equipment as the overhead crane.

Clothing changes can be a particularly fruitful source of lost time and in this regard emphasis has already been placed on the necessity for accurate and comprehensive records and the desirability in many cases of adopting a scheduled changing of wires and felts. The actual procedure for changing clothing is frequently made unnecessarily lengthy by inadequate preparation and the tendency to gather too many men round in the belief that this hastens the process. The routine for changing each piece of clothing should be carefully thought out, and is worth close examination using method study techniques. In arranging a wire or press part considerations of clothing change form a basic requirement affecting the engineering design, and close thought is always necessary to make certain that no inherent difficulties are likely. But even so it is inevitable that there are some snags on any machine and it is in overcoming these by provision of special changing equipment and brackets for fixing to the machine that some ingenuity is required. When the mill organization permits it, it is preferable for the clothing changes to be carried out by the same gang of men who specialize in this. When clothing changes are, as is usually the case, the responsibility of the machine crew who happen to be on shift, then the quality of supervisory personnel, careful designation of individual duties, and the training given to crews are most important for ensuring efficiency.

6B.1 2 Improving operational efficiency

However well-trained the crews and however carefully defined the working procedures, loss of production and waste still occur due to inadequacies in the equipment and in the general machine conditions. With regard to equipment, the isolation and recognition of the causes of downtime on the

machine, as discussed in **6A.1 2**, assist in pinpointing the trouble spots, but the aim should be to prevent these occurring in the first place. Poor making conditions are manifested in quality deficiencies leading to out-of-specification paper and broke and even contributing directly to downtime.

Breakdown of equipment can be completely unpredictable, but on the other hand there is no doubt that a sound preventive maintenance and inspection programme dramatically reduces the likelihood of it occurring. Gradual deterioration of performance causes trouble that is more difficult to avoid (especially when it appears as heavier vibration and increased variation of drive output) and can be very hard to detect when it becomes responsible for introducing weaknesses in the paper web that create breaks in another part of the machine. A long-term aid in reducing the severity of this general problem lies in the keeping of careful and comprehensive records of each piece of equipment. These should include not only obvious details of date of purchase, spares kept, lubrication and servicing, location of drawings, and so on, but also a careful tabulation of repairs made and any modifications introduced. This sort of information becomes particularly invaluable whenever a quick repair is needed.

Paper machines, in comparison with other pieces of industrial equipment, last a very long time and during their lifetime are likely to undergo numerous alterations and increases in running speed. This is inevitably a serious source of trouble because at any one time there are likely to be several parts of a machine seriously overstrained and approaching the time when their renewal is imperative. When this eventually takes place, and whenever a major modification is made to introduce a new lease of life to an old piece of equipment, a record of this change should be kept in a special book devoted to the machine as a whole. This general record of major alterations can be very useful in identifying changes in operating conditions which subsequently become noticeable in the long-term data provided from machine tests, breaks and production analysis, and quality records. In this connection data going back many years can occasionally be found to give an important clue, and investigations are assisted by having all these various records available in a similar form and averaged when appropriate over the same three or six monthly periods. During enquiries it is frequently found that instrument and other charts relating to machine conditions would be helpful but these have long since been jettisoned because of the space they take up. A useful compromise is to arrange to retain charts and detailed records covering, say, a couple of weeks during two characteristic periods of each year. It is then possible to get a general picture of the operation at different times in the past and extract data that might not hitherto have been thought worth keeping.

Occasionally it is a useful exercise to make a general analysis of a particular paper machine system for comparison with other machines. This is a task which is necessary when any general reconstruction is under consideration and can be most valuable if carried out in conjunction with one of the major machine suppliers who have a wider range of experience in the use of equipment for making different classes of paper at different speeds. Such an analysis would involve a detailed examination of the

584

function and condition of each piece of equipment, and the present performance in such matters as power and speed in relation to the original specification. At such times it would also be appropriate to draw on downtime records for information and to determine the economic possibility of renewal (see **6B.2 5**). Especially with the stock preparation system, a detailed flow diagram and an analysis including power and manpower requirements and the flow of work through the building is also useful for an overall examination.

Quality deficiencies are generally caused by excessive process variation as a result of poor control of the system and the lack of defined operational procedures. Several specific aspects of this have already been discussed, for example in relation to starting-up, shutting and changing grades. Other relevant matters such as the control of cross-web variation and obtaining as high a moisture content at the reel-up as possible have also been dealt with. It is obvious too that much of the effort directed at reducing downtime from faulty equipment will have a beneficial side-effect in reducing quality variation. Reduction of machine direction substance variation is an important item in this context. This is partly because lower substance fluctuations tend to reduce variation in practically every other property, but also it becomes simpler to attain a mean substance closer to what is required. This can present a substantial economy over a long period since (in the face of high substance variation) there will inevitably be a tendency to produce a sheet slightly on the heavy side both to make running easier and other properties less likely to fall below standard.

There are several other general points relating to improvement of operational efficiency that are worth mentioning. Excessive trim loss can become too easily tolerated and this represents an appreciable wastage. Modern approaches to trim reduction by applying linear programming techniques are well worth investigation though there are still a great many problems in their general application. Sometimes the problem of trim waste is aggravated by too great a variation in the deckle of rolls coming off the machine, a result primarily of changes in shrinkage rate in the dryers. When this cannot be reduced sufficiently, consideration should be given to closer control and the use of expander rolls.

It is customary to strip a certain amount of paper from the top of each roll because the outer few layers can become saturated with water or unevenly wound and creased during the change. Unfortunately this routine readily seems to arouse some primitive stimulation from using a knife and many more layers are stripped off than is necessary. This common habit can come to represent a substantial wastage of good paper and it is worthwhile giving consideration to providing a special knife with a form of runner or some device which prevents cutting below a relatively small depth. Whenever a single shallow cut is insufficient to remove damaged surface paper, it is not troublesome to strip off a further layer.

The need to keep a check on the overall fibre wastage from a machine system has been touched upon, and this is one source of loss that can often be reduced quite simply with a little thought. The reduction of fresh water entering the system in pump glands, sprays, seals and so on will bring about

a proportionate reduction in the loss of fibre in the overflow. To be permanent it is desirable that water rotameters are provided in key positions and instructions given as to setting the flow.

Dirt in its various forms is usually responsible for some loss of production, either because it creates a break or spoils the appearance of the paper, and much of the trouble caused by this comes from poor housekeeping and inadequate cleaning. Insistence on a reasonable standard of cleanliness and tidiness in the mill not only contributes to reducing this loss but should also be psychologically beneficial, a matter too often underestimated in importance. In this respect the mill management can also assist by such small but valuable items as arranging frequent painting of walls and machines, keeping working conditions tolerably comfortable, tidying up areas of the mill which have become disused, and other obvious ways relating to the welfare and comfort of machine crews.

6B.2 FINANCIAL CONSIDERATIONS

Decisions to replace equipment or to run a new grade have aspects which are obviously financial as well as technical. To a lesser but nonetheless important extent, the running of a machine faster or with a different furnish or with less broke is not just a matter of technical feasibility but has an important bearing on the economics of the process. This is the subject of the present section: how, to put it simply, is it possible to put a value on making a change in the system?

Proper cost data for a paper mill, and particularly for the machine itself, is essential for giving a realistic estimate of the economic potential of making changes to operating methods and equipment, and of running new grades. The same data assists immeasurably in assessing the comparative worth of different proposals and it can also help to indicate areas and operations which are ripe for improvement in efficiency. The most common form that such cost data takes is known as standard costing and this is discussed first, followed by examples of how the standard cost figures derived can then be used to put a value on different operational changes. Of these, the installation of a new piece of equipment requires particularly careful costing and this is given special attention.

6B.2 1 Standard costing

The basic principle of the standard costing system is a simple one. It involves first the splitting of all costs to various centres and the relating of these to the total cost of producing a ton of each grade of paper. These costs are collected over, say, a six monthly period to give a reasonable average for each item and thereby take account of fluctuations from week to week in machine efficiency, maintenance requirements, accidents to clothing, and so on. The figures derived over this period are then taken as the basis for predicting costs for the coming period, with due allowance made for known variations which are expected to occur (for example, an increase in pulp prices or running at a higher machine speed as a result of some alteration just taking place). These figures then represent the standard

costs for that period and their main use is to act as a standard against which to compare actual costs incurred, the difference (or variance) figures being used to indicate the need for investigation in the event of actual costs being appreciably different from those anticipated. Standard cost figures are also used for a variety of other purposes such as budgeting, planning capital expenditure, and (of specific interest in the present context) for permitting more accurate estimates to be made of the value of operational changes in running the machine.

The most difficult step in working this system of costing is to decide on the different cost recovery centres (i.e. functions costed separately) and the extent to which relatively small variations in costs between different grades or finishes are taken into account. In what follows it is proposed to give an illustration of the sort of breakdown that can be adopted for the most general case: a multi-machine mill with its own pulp preparation and finishing plant. In deriving this, information and suggestions from several sources have been used, notably references (4), (5) and (7).

The first point to clarify is the distinction between fixed and variable costs and this is done most simply by giving examples. Fixed costs are, in effect, overheads that are unchanged whatever grade of paper is made, and indeed whether paper is made at all (at least over a reasonably short period). They include the cost of such items as depreciation on buildings and equipment; rent, insurance and rates; general office and sales expenses and salaries; laboratory and other technical services; ancillary services such as security, first aid, welfare, sports and canteen; direct labour for machine crews and associated operatives in the preparation and finishing plants; packing, storage, handling and transport facilities; and material and labour involved in machine maintenance and repairs including depreciation of engineering equipment and stores charges. Other fixed costs will include similar charges for units such as bleaching plant or coaters used by a proportion of the grades of paper made in the mill and chargeable only to these grades.

Variable costs are all those charges which have a direct relationship to the quantity and grade of paper actually produced. They comprise costs for raw material, including chemicals and loadings; steam, power and watrr supplies to pulp and paper preparation plant and the machine (though see page 591); coating, size and other materials used in after-processes; non-returnable centres, wrapping and packing materials; and despatch and carriage charges.

The relation between the fixed and variable cost contribution for a particular grade affects the value of making different improvements to the system. For instance, if variable costs account for the larger proportion of the total costs, then reduction in charges for such things as furnish and finishing can have a very important significance. By contrast, when fixed costs are relatively high an increase in production can be more valuable because this spreads the overheads over a greater tonnage. These points will be considered in greater detail below.

Costs derived from individual centres can be used to build up a picture of the change in cost of a product as it passes through the mill. The

original raw material cost is increased to a slightly higher cost by the time it enters the pulp preparation plant due to the storage and handling it has undergone. When pulping is complete, further costs have been involved in labour, supplies, services, maintenance, depreciation, etc., and this continues through the stock preparation plant, the paper machine itself, and finishing. Each part of the process involves further cost and so, in effect, adds to the value of the product at that point. This is the 'added value' concept. It might better be termed 'added cost' because the value that can be attached to something depends on market conditions.

The 'added value' can even be found for such processes as formation on the wire, pressing, drying and on-machine sizing, as well as for distinct operations, like supercalendering or off-machine coating. This involves taking certain arbitrary decisions regarding such matters as the splitting of maintenance and supply costs, but is nonetheless a straightforward exercise if the necessary data is available. For instance, Holt (5) performed this calculation 'at considerable labour' for several machines in a pulp and paper mill and found that the relative costs were greatest, surprisingly, for pressing ($14,58 per ton), then formation ($12,36 per ton) and then drying ($11,94 per ton). The main reason for the relatively high pressing cost was due to high supplies (mainly felts) and services, though the fixed charges based on original capital cost were also high.

A different type of cost analysis of the Fourdrinier has been made by Barbour and Tweedie (10) who presented figures showing that typical operating costs per hour (steam and power only) to run the dryers of a machine are far higher than similar costs for the wire, which in turn are higher than the presses. Related to the quantity of water removed the order of costs involved changed to dryers highest, then presses, then the wire part.

Other figures presented by these authors show that the initial capital cost of a machine per foot of length varies little from one section to the next, so as dryers are the longest once again costs are highest for this part of the machine. Holt also looked at the capital cost of a machine from the point of view of deckle, and reached the conclusion that there can be an optimum width above which it is uneconomical to go.

The value of data such as this is more useful for comparison with other machines than in the costing of an individual machine where it is not particularly relevant to know the individual costs of separate parts of the process when these are completely interdependent. Compared with other machines, however, it may be possible to gain an indication of where technical improvement could most usefully be sought, though in this respect comparison of downtime and performance figures would usually be more relevant and simpler to compile.

6B.2 2 Cost centres

The division of costs into fixed and variable is not always so easy as it might at first appear. When there are several machines in the same mill sharing the same services and perhaps the same pulping and finishing plant, costing machines separately presents some problems. It is appro-

priate at this point to consider one or two aspects of the derivation of cost figures in more detail.

In the first place, choice of cost centres has to be made very carefully. The precise selection depends entirely on the system, but as a general principle it is important to be able to cost separately such distinct operations as supercalendering, coating, dyeing, laboratory services, instrument department, in fact any part of the mill which makes a clearly-defined contribution of one sort or another. Excessive analysis has, of course, to be avoided, and the possible use of each individual cost in controlling future expenditure, costing new lines, and in assessing the value of modifying the process must always be borne in mind. In the manufacturing plant itself, there is little point in costing separately any part of the process that cannot be by-passed, provided data relevant to operating conditions (power and steam usage, maintenance time, etc.) can be obtained for analysis if necessary.

The different costs involved can be considered under several headings, and it is usual to take the paper machine itself as the main basis. There are, firstly, the fixed charges on the building and equipment including rent, insurance and rates. Where two machines share the same building, combined costs would usually be allocated according to area. Where pulp preparation, paper preparation, and finishing plant are shared, cost-splitting to different machines and grades (of all fixed charges including those discussed below) can be on a time utilised or tonnage basis, whichever is most appropriate.

Depreciation on capital cost of manufacturing equipment presents some accounting problems because if the practice is followed of writing off a fairly high percéntage in the first year, then on paper a new machine will often make a heavy loss. One method suggested (7) is to have nil depreciation in the first year, $2\frac{1}{2}$ per cent. for the next two years, and only then rise to the normal tax-allowance levels of $7\frac{1}{2}$ per cent. and 10 per cent. of value. However, the precise manner and rate at which capital is discounted is a problem for the accountant, and as current government legislation allows an immediate refund in tax relief of between 20 and 45 per cent. of the capital expense it is now possible to allow greater depreciation in the first year.

To these basic fixed charges are added all the operating overheads from each of the service departments: engineering, electrical, instrument, general office, sales, personnel, transport, laboratory, work study, and so on, together with the various ancillary services. These overheads comprise depreciation of buildings, labour costs, stores, and general running costs for each unit. The total of these can be regarded as common to the mill, and must then be apportioned to the various units of the manufacturing plant as an addition to the basic fixed charges. The way this is done depends on many factors including tonnage and value handled, number of operatives involved, capital cost and age of equipment and so on; a certain degree of arbitrariness is bound to creep in and decisions of this type must depend largely on the detail available. For instance, in addition to individual overheads and direct labour costs, it should be possible to charge main-

tenance costs involving labour, time and materials to each manufacturing unit separately (coating, alum plant, bleaching, sizing, etc.), so that proper account can be taken of the true cost of these facilities when they are used for particular grades. Under this heading would be included clothing costs for the machine and other items requiring regular renewal such as Sheehan ropes and suction box covers. Specialized equipment such a roll-grinding machine should really only be charged to the units making use of the facility.

So much for the fixed charges. With these an accounting period of one year allows the inevitable weekly cost variations caused by sudden repairs or replacements of an expensive piece of clothing to be smoothed out. The fixed charges for each machine can be used to produce an hourly standard running cost, on the assumption of a known number of working hours each week.

Variable costs are principally those for raw materials, supplies of various kinds, and materials used in finishing and despatch. Water may also be included as a variable cost though variation in this from one grade to another would not usually be of significance, so it is simpler to treat water costs as a fixed charge. Raw material covers pulp costs, either as the price of bales or of raw materials plus the separate cost of pulping, together with other additives such as alum, resins, dyes, loadings and other chemicals for bleaching, wet-strengthening, pitch dispersion, and so on, the cost for each of these taking into account the cost of preparation. Materials used in finishing and despatch include coatings, sizes, wrappings, etc. It is evident that reasonable accounting of variable costs is only possible if accurate figures are known for consumption of all these materials. For instance, it is important, especially in multi-machine mills, that appropriate meters are available on such common lines as those supplying steam, liquid alum, and other continuous additives to the machines. Power used in the preparation plant, on the machine, and in finishing processes must also be known.

The main variable cost is, of course, the pulp itself and certain difficulties can arise in accounting for consumption of this. Generally speaking, when bales of pulp are used it is necessary to weigh each of these individually, classified according to type, and correct for a previously determined average moisture content. When pulp is prepared in the mill measuring the quantity passed to the paper machine for a particular making is not so easy unless it is the custom to dry the pulp and store it in steeps. In this case determination of moisture content of the pulp and checks on the weight of loads taken to the beaters can be used to give a reasonably accurate measure. Otherwise resort has to be made to flow measuring devices and consistency measurements, or to an accurate determination of fibre drained to waste.

Broke also presents a problem, especially when it is kept for long periods for use in specific makings. It is possible to take account of broke made during a making and offset the value of this, but usually the quantity of broke it is possible to use in the furnish cannot alter much from one making to the next and it is possible to discount it completely from the costing point

of view. Over a number of similar makings, variations in the quantity of broke made and re-used should average out sufficiently to be absorbed with the other variations that occur. Only when broke is switched from one machine to another or re-used for different grades is it essential to keep an accurate account of the tonnage involved and to attach a definite value to it.

When a mill produces most of its own power and steam requirements costing of these, even when usage is accurately known, requires careful thought. The overheads and running costs of the boiler plant can be apportioned to the machines and other manufacturing units in accordance with either the actual process steam usage or the amount that has to be available when required (a sort of standing charge), or a combination of the two. Similarly the cost of steam engine or turbine plant can be apportioned according either to actual power usage or to the provision necessary, or both. These costs can be presented as fixed charges to the manufacturing unit based on average usage over the accounting period. The coal used in the boilers is not quite so simple to deal with because the steam it provides is in many mills used for both power generation and process heating. A reasonable compromise is then to split the coal cost on an average heat drop basis, i.e. in accordance with the amount of energy used up for the two functions, and arrive at separate charges for process steam and power steam usage. The full cost for out-of-balance steam would be charged to the function responsible, e.g. to the engines or turbines when it is necessary to blow off some steam not required for process heating. In a mill which does not generate its own power, running costs are obtained directly: the coal consumption for process steam and the local electricity board charges for power. These costs for process steam and power can be added into the other fixed charges, but when steam and power consumption vary considerably from one grade to the next, it is obviously preferable for them to be treated as semi-variable charges, thereby giving more accurate data for arriving at comparative costs of different grades. Provided a mill possesses reasonably accurate steam and power distribution records, there is no difficulty in this and it also accords more with reality for even when a machine is shut it is then still charged with overheads incurred in the boiler and turbine plant but not with the steam and power it does not use.

When different makings follow one another in quick succession on a machine it is not practicable to keep separate account of supplies used for each individual making. Normally makings of similar grade and substance would be grouped together, and variable costs assumed the same for each, account being taken only over the complete succession of makings in the same group. Provided it is reasonable to assume there is no significant change in such features as the refining, pH, retention on the wire, or the steam consumption per lb. paper, this practice is perfectly satisfactory. The same principle can apply equally to grades differing only by small degrees of pulp composition, loading content or dye addition, because the different costs involved in changes of this type are readily accounted for.

From records of the average tonnage made per hour, the fixed charges (in which costs are per hour) and the variable charges (in which costs are

normally recorded per ton) can be brought together for each separate grade. An overall picture thus emerges showing precisely how the cost of each grade is built up. When these costs are compared one grade with another discrepancies will inevitably appear. Sometimes these differences between similar grades are perfectly legitimate, as for instance when a particular making requires a prior wash-up so downtime for this reduces the machine time efficiency. In other cases differences may be more difficult to account for but nonetheless fair, for example when a slight alteration of furnish leads to an increase in trouble from pitch. But it is quite possible also for discrepancies to arise by accident, as for example when a bias is introduced because a particular grade is always run first after starting up (and is therefore more liable to inefficient operation) or because another grade is always run towards the end of the week when there are liable over a period to be more stoppages for felt washing or wire repairing. The different costs thrown up in such cases unfairly load the grades concerned and should really be discounted, but often it is very difficult to be certain when differences are in fact caused by such matters. Other cost differences arise when certain grades are repeatedly run only for short makings due to a greater proportional waste of pulp and loading (in cleaning out after the making) and of time spent at the start of the making in achieving correct quality. Such differences are, however, a perfectly fair reflection of the true making costs. These aspects of machine operation will be investigated in greater detail in **6B**.3 where the various differences that can appear between the operational efficiency of one grade compared to another are examined.

6B.2 3 Costing improvements to the paper machine

It is now appropriate to consider some of the ways in which standard cost figures can be useful for costing improvements and alterations to the paper machine. With certain alterations, such as change in furnish or coating mix, or a reduction in labour force, it is comparatively straightforward to calculate their influence on the overall cost of the end-product. But in other instances, such as those involving increased machine speed, reduced broke or downtime, or increased selling moisture content, a little care is needed to evaluate the true effect on the costing figures.

To illustrate these points it is proposed first to present some purely hypothetical cost figures which, for simplicity, are taken to represent the standard costs in a mill generating its own steam and power and making an uncoated and machine-finished grade of paper prepared from bales of pulp and despatched direct in reel form. This gives a rather higher relative furnish cost than would be usual in many mills but this means that the economic effect of the improvements examined is not exaggerated and can in fact be regarded as closer to the minimum relevant for the particular selling price concerned. (In practice costs would be available for a variety of grades and a weighted average of these might be taken based on the anticipated production requirements on the machine for each grade.)

It is assumed that the machine output of saleable paper related to the total available hours is 2 tons per hour, that broke amounts to 13·33 per cent. of production off the machine, that the standard week (i.e. the time

available for making paper after a reasonable allowance for starting-up and shutting) is 130 hours, and that average downtime on the machine amounts to 10 hours per week. This in fact means that the machine produces paper at the rate of 2·5 tons per hour for the equivalent of 120 hours of the week giving a total output of 300 tons of which 13·33 per cent. or 40 tons is broke and the remainder, 260 tons, is saleable. Standard costs are:

							Standard Costs	
							£ per ton	£ per hour
Mill overheads (offices, sales, insurance, services, rates, etc.) ..							6	12
Depreciation of equipment and buildings	..	..	..				5	10
Direct labour	..	..	..	..	..	..	4	8
Maintenance, repairs, clothing	..	..	..	..	..		4	8
Boiler and turbine plant	..	..	..	..	..		3	6
Total fixed charges	..	..	..	..			£22	£44
Pulp ..	..	..	..	..	..	..	50	100
Loadings and chemicals	..	..	..	..	..		8	16
Finishing, wrapping, storage and distribution, etc.				..	..		7	14
Coal for process steam and power	..	..	..	..			3	6
Total variable charges	..	..	..				£68	£136
Manufacturing costs (from above)	..	..	..	..			90	180
Profit	..	..	..	..	..	..	10	20
Selling price ..	..	..	..	..	..	..	£100	£200

With these figures it is now possible to investigate the financial effect of various improvements that can be made to the operating conditions. First, what is the situation when an increase of 1 per cent. in speed is achieved? If other conditions are unchanged, i.e. there is no alteration in downtime nor in broke ratio, and also no additional maintenance and clothing needed as a result of running faster, this yields an additional 1 per cent. of 260 or 2·6 tons per week of saleable paper. Now it must be assumed at this point that this additional output is in fact saleable, in other words that order books are full and demand exceeds (or with a sales drive can be made to exceed) current capacity. This is a central point in all the cost considerations that follow, except for that applying to increased moisture in the paper, because in all other cases an actual improvement in output occurs. In the circumstances when capacity exceeds demand a higher output may simply mean shutting a machine earlier in the week with little resultant savings. If this is the present situation, or is predicted for the near future, then obviously any plans based on raising production would be very much less likely to prove fruitful.

A straight production increase of one ton in the week will give an additional profit equal to the difference between the selling price and the sum of variable expenses. This is obvious because all the fixed charges have already been absorbed in the calculation of standard costs based on current output. The variable costs represent what has been termed the marginal cost for small production increases, in other words the additional cost incurred for each extra ton produced. The smaller the proportion of variable costs in production to the selling price, the greater the additional

profit from increasing speeds. In the example, the additional profit per ton is £(100 − 68) = £32, and for a 1 per cent. increase in speed or 2·6 tons per week, this will amount to 2·6 × £32 = £83·2 per week. This represents a 3·2 per cent. increase in the total profits of £2,600 per week.

A similar case is presented when downtime is reduced. This also has the effect of increasing output, but the additional profit from each extra ton is very slightly higher than when brought about by a speed increase. The reason for this is that when a machine is down a certain amount of steam and power is consumed to keep drying cylinders warm and turn different sections over. This might amount to a coal usage of about one-third the normal consumption when producing paper. Consequently, the marginal cost for an additional ton of paper is in this case equal to the variable costs (£68) less the coal cost during downtime (one-third of £3), giving £67. Additional profit per ton is thus £(100 − 67) = £33. A 10 per cent. reduction in downtime from 10 to 9 hours per week will make available 2 tons of paper and so increase profit by 2 × £33 = £66 per week.

Reduction in broke from improved deckle distribution, more consistent quality, and so on has a different effect on profits. In this case the saving (other conditions being assumed unchanged) which results from having a ton of saleable paper instead of a ton of broke is the cost of reprocessing the broke to make it saleable. This is, in effect, the total cost of producing the paper less the cost of the furnish which the broke is substituted for, i.e. £50 for the pulp plus £8 for loading and chemicals. The cost of producing the paper is the total manufacturing cost (£90) less the finishing costs of £7 which have to be incurred anyway (unless the broke is from the salle in which case it is actually less than £7). The saving is therefore £(90 − 7) − £(50 + 8) = £25 per ton. Additional profit on the ton of saleable paper is this saving plus the usual profit of £10, i.e. £35. A reduction of 5 per cent. in the broke level from 40 to 38 tons will make available a further 2 tons of paper which will increase profit by 2 × £35 = £70 per week.

This calculation assumes that quality of the broke is as good as the original furnish and that the cost of breaking down the broke and adding it to the system is not significantly different from the cost of breaking down and treating bales of raw pulp. The latter supposition is not unreasonable for the order of accuracy it is possible to achieve in this sort of calculation, but the equivalence of the broke to the original furnish is unlikely. A better approximation of the true saving from reducing broke is to assume that it normally takes the place of the cheapest and weakest constituent of the furnish, e.g. mechanical pulp in a printing or news grade, and requires the addition of some loading to make up for retention losses. The broke, in other words, is less valuable than the calculation above assumes, so the saving will in fact be greater than £25 per ton.

As a final example, consider the effect of obtaining a 0·5 per cent. increase in the value of moisture content of the saleable paper. This is an exercise more relevant to paper sold in reel form, but to a lesser degree it is also pertinent to paper sold in reams. An increase of 0·5 per cent. of moisture in effect substitutes water for the same amount of furnish in the paper. The saving, other conditions being equal, will thus be 0·5 per cent.

of £58 or £0·29 per ton of saleable paper. There will also be a small additional saving in steam consumption if the moisture increase is achieved by drying to a higher value at the reel-up, but if it is added in later the opposite applies. For a weekly output of 260 tons, the additional profit from an increase of 0·5 per cent. moisture in the paper is therefore 260 × £0·29 = £75·4 per week.

Summarising the four calculations above:

Improvement in operating conditions	Additional profit per week
1 per cent. increase in speed	£83·2
10 per cent. reduction in downtime ..	£66
5 per cent. reduction in broke	£70
0·5 per cent. additional moisture content	£75·4

In other words an additional profit of about £100 per week will be derived from each of the following alternatives:

(i) increase in speed of 1·2 per cent.
(ii) reduction in downtime by 15 per cent.
(iii) reduction in broke level by 7 per cent.
(iv) raising moisture content by 0·65 per cent. moisture.

It is instructive to ponder the implication of these figures, which are by no means untypical. The value of a little extra water in the paper is particularly revealing, and reflects the relatively high furnish cost which causes any small reduction in furnish requirements to make a large contribution to profits. A modest increase in speed and quite a sizeable reduction in downtime, both of which are often not so easy to achieve, make a similar contribution to profits. Such data as these should be available for all paper machines and are obviously of crucial importance to any plans for improving performance.

6B.2 4 Installing new equipment

New equipment is installed for a variety of motives, sometimes purely for its psychological impact on machine crews or for the benefit of a particularly awkward customer. If the circumstances demand it, there is nothing inherently wrong in this. But whatever the situation one thing should be clear, and that is the cost of carrying out the operation. For any new piece of equipment a clear picture of the financial implications should be drawn up before the order is placed, and afterwards the accuracy of this picture should be checked so that lessons are learnt from the inevitable mistakes that occur.

Many things contribute to the successful introduction of a new piece of machinery and can have a big impact on the eventual financial benefit of the operation, so it is appropriate first to devote a few words of general comment to this topic. It is of course obvious that full details of any new equipment must be obtained before a decision can be taken to purchase it. These details must cover points such as maintenance requirements, servicing arrangements, commissioning agreements, services needed, supply of all ancillary equipment, and a full technical specification. Design and use of the equipment must be considered by the engineering and production departments, and at an appropriate time electrical, instrument,

maintenance and other departments should be given the opportunity to comment.

Where several different types and design of equipment can fulfil the same role, a detailed comparison must be drawn up and many aspects looked at apart from the simple ones of price and delivery. Inspection of the equipment working in other mills is frequently of benefit if only because a much clearer idea is obtained than comes from examination of drawings and photographs. The paper industry is blessed by a particularly co-operative attitude in these matters and the mutual benefit that can in the course of time be reaped from allowing visitors is recognized by all but a few insular (and almost always old-fashioned) mills. Information from impartial sources such as the British Paper and Board Makers' Research Association can also be invaluable at this stage. Occasionally it is possible to borrow the equipment from the manufacturer and when doubt persists this can be a useful way of postponing judgement until as much information as possible is available.

Once a decision to purchase has been made, the preparation work and other equipment that has to be ordered or fabricated at the mill should be listed, and a programme devised for carrying out the whole operation. At this point it might be beneficial if the job is large enough to decide on man-power requirements and draw up a critical path analysis for carrying out the installation. Similar considerations can be brought to the actual timing and placing of orders for different parts of the ancillary equipment in order to prevent tying down capital unnecessarily early. In this respect, however, the potential loss from not being able to complete a job for lack of some small and relatively inexpensive component generally makes it advisable to leave an ample margin over the suppliers' estimated delivery times. As the various items arrive at the mill rigorous inspection against drawings and specifications is advisable. The position regarding spares must be con-sidered and adequate safeguards taken to carry a suitable stock.

It is also important at this stage to take every opportunity to acquaint other members of the production staff and machine crews with the im-pending installation of new equipment. If necessary, time has to be devoted out of normal shift hours to explaining the purpose and operation of the installation. This is not only more likely to secure the eventual interest and co-operation of the operators, but involves them in the project at the outset and makes it clear they have some responsibility for its success. When the time comes for perseverance and ingenuity in the face of those problems which arise with any new equipment, the attitude of the production personnel makes a considerable difference to the speed and effectiveness with which a solution is found. Discussion of the new equip-ment with operatives is also likely to produce points of view which had not previously been thought of, and refinements may be introduced which eventually save a great deal of time. It will also be valuable when compiling for the benefit of supervisors and operatives a general information notice and operating instructions—an absolutely essential task.

With any new piece of equipment some changes in operation of the whole paper machine system and of the paper quality are to be expected

and assessment of these is important. It is no use requiring tests to be taken of appropriate properties when the equipment has gone in; this must obviously be done beforehand as well, so the implications of the new equipment must be discussed with the mill laboratory and a suitable programme of tests devised. Generally speaking, a straightforward before and after comparison does not present any problems in experimental interpretation though care is needed when the values of some properties are not at a static level but are subject to a steady trend resulting perhaps from a continual programme to improve quality. In the latter case, so long as information is available for a number of individual occasions, and this is one advantage of comprehensive long-term records derived from complete system checks, then graphs can be drawn showing property values over the period spanning the installation and these should make it unlikely that incorrect conclusions are drawn.

Once the equipment is installed comprehensive tests may be necessary to ensure it is operating in the most beneficial way, and that performance is up to specification. This may require a series of checks to be made with operating variables at different levels in order to determine optimum conditions. Analysis of variance techniques can then be applied to give a correct statistical assessment of the results. Occasionally there will be danger of causing a loss of production by carrying out this more formal type of experiment and then other techniques of evaluation, such as Evolutionary Operation and its offspring Simplex Evop, can be employed. Failing all else, evaluation of the effect of running with different operating conditions can be made by examining the accumulated data of ordinary production runs. In this case multi-regressional analysis is a valuable statistical tool which can pick out the most important variables from a large number and assess their effect on the property in question. The tedious calculations formerly needed before this method could be applied are now obviated by the use of straightforward computer programmes.

Routines for maintenance, lubrication, servicing, operating tests and general inspection of the new equipment by papermakers, engineers, electricians and so on should be worked out to reduce to a minimum the likelihood of lost production from future malfunctioning. Manufacturers are usually only too willing to help with this task because trouble-free operation is as much in their interests as the mill's. It is unfortunately too easy to neglect new equipment once its initial novelty has worn off and it appears to be giving a satisfactory performance. But a thorough post-mortem is necessary some time not too long after the installation has been satisfactorily completed, and this is an appropriate time to carry out revision of operating maintenance instructions in the light of experience, and note down modifications made to the original design. At the same time a full report on the operational benefits and financial gain should be drawn up to guide future installations.

6B.2 5 Costing new equipment

Before any new piece of equipment is purchased a thorough assessment of the financial implications should be carried out. This may be done in the

very early stages purely as a feasibility exercise to see if the project ought to be taken further. In this case the estimated cost for the installation might be based only on budget prices and subject to considerable error, but the method of approach is still basically similar. If the exercise is performed after the equipment is working satisfactorily, then a really complete and accurate picture is obtained, but again the principal steps in evaluation are the same. These will now be considered.

It is useful to divide equipment costs into three parts: the costs of acquisition C, of operation O, and of maintenance M. In each case it must be understood that costs associated with any existing equipment which is being replaced are allowed for. Thus, the scrap value of old equipment and any spares should be subtracted from C, as should be current operating and maintenance costs from O and M respectively.

The cost of acquisition C comprises the purchase price of the equipment, plus any ancillary items that are required. Where new standby equipment is purchased or existing equipment for another purpose is utilized, then a part share of the cost of this determined on the basis of estimated use should be added. Installation and commissioning costs are also included, plus mill labour and materials used from the stores during erection.

Operation cost O comprises direct and indirect labour charges; power, steam and other services; insurances and licences; and the cost of space occupied by the equipment. Maintenance cost M comprises lubrication and cleaning charges; an estimate of repairs; and the cost of keeping spare parts in the stores. Costs for both O and M are taken over a year.

A fourth and most important item is the yearly saving S which is found or anticipated as a result of installing the new equipment. This can come under many headings and be relatively simple or difficult to determine depending on the complexity of the changes occurring or likely to occur. The profits from increases in machine speed or over-all production, reductions in downtime or broke, and increases in moisture content have been detailed earlier in this section and are fairly straightforward. Putting a value on improved cleanliness of the sheet, better strength characteristics, and other quality benefits is an almost impossible task and depends entirely on mill conditions and relationships with the customers concerned. There are indeed circumstances when these particular factors outweigh all others and make an apparent increase in production costs worthwhile sustaining.

The four values C, O, M, and S can now be used to assess profitability of the new equipment. There are various ways of doing this and the usual one adopted (at least when trying to assess the potential worth) is the simplest, if only because the accuracy of some of the figures relating to expected improvements are inevitably hazy and make more sophisticated analysis rather pointless. Usually it is only possible to work out the profitability taking a reasonable view of the likely improvements, and for this experience and an objective element of judgement are needed to avoid being over-optimistic.

The easiest method is to determine the 'pay-back' period. This is quite simply $C/(S - O - M)$, which represents the number of years that must elapse before the initial capital outlay C has been repaid by the annual

profit of saving S less operating cost O and maintenance cost M. One year would certainly be regarded as really excellent, two as very good, three as reasonable, and four as nearing the limit of use of the formula for assessing the value of short-term investments. This method has the supreme merit of simplicity and is readily understood by operating personnel, even though accountants would advocate that it is treated with great care because it ignores interest, depreciation and other essential elements. However, as a means of distinguishing between the merits of different schemes or deciding the order of priority of different stages in a large project, it is certainly perfectly adequate.

A more sophisticated estimate of profitability is the MAPI method which defines the 'rate of return' on investment. In the first year this is

$$100[(S - O - M) + (C_1 - C_0) - D]/C_0$$

where C_0, C_1 are respectively capital values when new and at the end of the first year, and D is the depreciation over the year. The term $(C_1 - C_0)$ is included to take account of a rise in prices, otherwise the calculation amounts to determining the ratio between profit (allowing for depreciation) and original cost, and this is clearly a measurement of the rate of return.

An example will make these methods clear. Suppose we are considering replacing with more modern equipment some old inefficient screens which are always breaking down and running to capacity (occasionally limiting production). The total cost of the new screens is £10,500 and sale value of the old equipment is £500, so C or C_0 = £10,000. Additional operating cost amounts to the difference in power consumption which we will estimate is 20 h.p. or about £1,000 a year (assuming 2d. a kilowatt, continual working and 20 days shut a year). There is no change in direct labour costs or floor space required. Maintenance cost should be less and this is estimated as worth £500 per year. After one year it is reasonable to expect that the new equipment will be about 5 per cent. dearer or cost £11,000 but the old screens might then be only worth £300. Hence C_1 = £11,000 − £300 = £10,700. Depreciation on equipment of this type may be taken as pretty heavy, say 20 per cent. over five years. Finally (and this will be sheer guess-work) assume that an anticipated increase in machine speed coupled with reduced downtime and a little less broke work out at being worth £3,000 a year. We thus have C or C_0 = £10,000; O = £1,000; M = − £500; C_1 = £10,700; D = £2,000; and S = £3,000. Payback period is therefore £10,000/(£3,000 − £1,000 + £500) or exactly four years. The other formula gives a return of

$$100[(£3,000 - £1,000 + £500) + (£10,700 - £10,000) - £2,000]/£10,000$$

= 12 per cent. This would probably represent a marginal operation. The main merit in the second formula is that it takes account of changing circumstances and can sometimes illustrate the disadvantages of *not* taking any action. This is because allowance is made for the rising cost of new equipment and the lessening value of what is at present in the mill.

As an alternative to both these methods, a complete profit analysis can be undertaken assuming straight-line or more sophisticated rates of

depreciation over the years and allowing for tax concessions on capital equipment, interest payments on borrowed money and other financial implications of the operation. But this enters the accountant's sphere with a vengeance and he would certainly prefer to be consulted for a professional opinion.

6B.3 PERFORMANCE UNDER DIFFERENT OPERATING CONDITIONS

Very few machines continually make the same grade and substance of paper. On the vast majority a variety of grades are made during the course of a week, indeed the extent of this variety is a good index of the age of the machine. It is usual that a gradual progression takes place over the life of a paper machine from a single product made at (for the period) high speeds, to the time when the machine falters along making a succession of special grades in ever-decreasing tonnages. However, this does not necessarily imply growing inefficiency or smaller profit margins. Indeed, old machines can often make substantial profits if a suitable grade is found; low tonnages are no barrier to this, particularly as depreciation will be negligible unless charged on a replacement basis. But perhaps in this connection the accent should be on the word 'can', because profits founded on a basically inefficient process are apt to be ephemeral. It only requires another company with a more modern and faster machine to set out their stall and the source of profit vanishes.

In the foregoing sections various aspects relating to the improvement and costing of machine performance have been discussed, particular regard being taken to the general assessment of profit for any grade of paper run on a machine. It is proposed now to turn to a more confined but nonetheless highly important question: for a single grade of paper how does the profitability of running a paper machine depend on the substance and the machine speed? The situation in which a machine makes one or perhaps two grades of paper though a wide range of substances is very common, but not all of these substances are likely to be equally profitable. Likewise, if attention is confined to a single substance, it is not always best to run at the fastest possible speed. Discussion of the factors which govern changes in running costs at different substances and speeds, and identification of the most profitable lines forms the subject of this section.

6B.3 1 Machine conditions at different substances

As the substance of a particular grade of paper is raised, conditions under which it is made on the same machine alter. These alterations stem from two considerations. Firstly, limitations of the equipment force changes in operating conditions, and secondly at higher substance even of the same grade of paper certain properties become less critical so the specification usually in effect becomes less tight.

The best example of these two points lies in the beating operation. As substance is increased, an early limitation to production appears both in the capacity of the preparation system in respect of beaters or refiners and in the drainage capacity on the wire (which of course depends on the

degree of wetness of the stock). Accordingly, it is usual to find that the fresh stock is not so heavily beaten which implies that less energy per ton of paper is used in the beating process. At the same time the slower drainage on the wire resulting from a combination of wet stock and heavy substance forces a gradual compromise in the amount of backwater added for dilution. The graphs presented by Mardon (9) and reproduced in Figs. 6.1, 6.2, and 6.3 illustrate these changes.

The effect of reduced beating per ton is clearly a lower development of potential strength in the paper, together usually with a change in the value of several other properties such as porosity. In other words, if standard
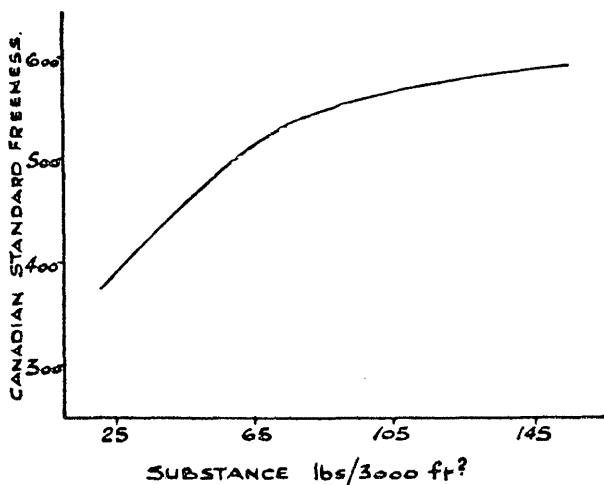
Fig. 6.1. Relation between substance and freeness of fresh stock (after Mardon)

hand sheets are made from the fresh stuff, for papers of higher substance these are the physical changes which would be found. But as a direct result of the rise in substance, strength, air resistance, and other properties of the sheet will also have higher values without any change being made in the degree of beating. So unless the particular grade demands a *pro rata* increase with substance in these properties, which would be unusual, it is quite possible to reduce beating and accept only a relatively small change in the properties. Greater substances are frequently demanded purely for handling and prestige purposes, and clearly when this is the case there is no value in increasing such properties as strength to greater levels than the basic minimum required.

Changes of this sort in the operating conditions can have an important effect on the speed at which it is possible to run a machine when making a particular substance. But apart from this it is obvious that there are several other specific restrictions which can limit the speed. The limitation in any particular circumstance may, for instance, be the main drive motor speed, or it may be drying capacity, preparation plant, open breast box height,

drainage on the wire, open couch draw tension, or quite a number of different factors. It is instructive to consider how these limitations for different substances can affect the maximum possible machine speed.

A good analysis of this has been given by Chedzey (1) who was interested basically in defining standards for a paper machine in order to apply work study bonus techniques. Although this motive would not find much favour these days, the methods of deriving theoretical limits are still highly relevant both as a means of comparing actual speeds with those which should be possible for different substances, and also for the present purpose of determining potential profitability. Assessing the maximum potential of a machine under different limitations can be fairly complex and it is not
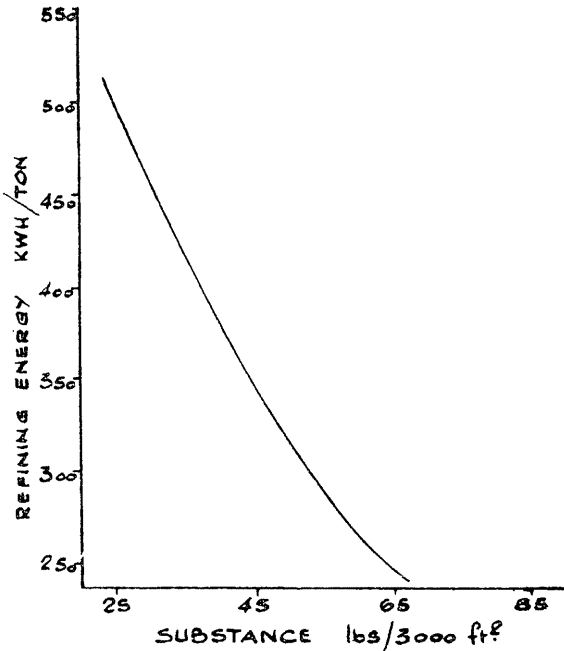
Fig. 6.2. Relation between refining energy consumption and substance (after Mardon)

proposed to go into the details here. As an example, Fig. 6.4 reproduces the calculated theoretical maximum speeds on a machine making mechanical printings and wallpapers due to limitations in drying capacity. The curve is derived from an assumption that drying capacity is constant, so that substance × maximum speed must also be constant, but also takes into account changes in moisture content of the web entering the dryers at different substances. It is also known, however, that in the later dryers evaporation rate decreases as the thickness of paper increases due to the difficulty of conducting heat through a greater bulk of dried fibres; hence it is likely that if extended far enough the curve should in fact show a downturn at higher substances.

Fig. 6.5 shows a composite graph derived by Chedzey for a wide substance range in which two other limitations to machine speed, those of breast box height and preparation plant are also included.

Variations in the maximum running speed as a result of these limitations obviously mean that the maximum possible production level changes also. Fig. 6.6 shows a graph drawn up by the author to indicate how production might in fact alter with substance over a fairly wide range. Being purely hypothetical and illustrative no scales are shown, but the curve is derived from Fig. 6.5 and is labelled to identify the specific limitation in successive
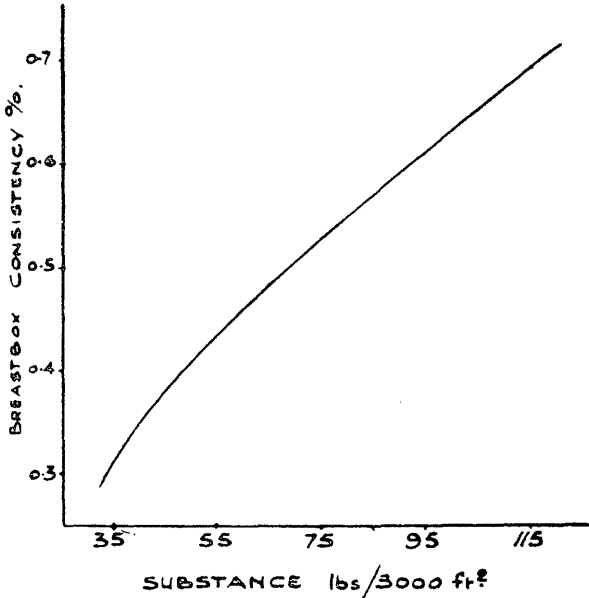
Fig. 6.3. Relation between breast box consistency and substance (after Mardon)

substance ranges. Here speed of the main drive motor is taken as governing the upper speed limit (this being a more common reason than breast box height), while allowance is also made for an important limitation pointed out by Mardon (9), that of web strength at an open couch draw which could necessitate reduction of speed at very low substances.

The fixed costs per ton will vary through the substance range approximately in accordance with the inverse of the actual tonnage produced. In other words the graph in Fig. 6.6 could, if turned upside down, represent the relation between cost per ton and substance. But allowance has also to be made for the fact that relative sorting and wrapping costs are dearer for lower substances (because of the greater number of individual sheets cut per ton). Further, at higher substances steam costs per ton are greater due to the decreased evaporation rate, though possibly this effect would in

practice be offset by reductions in maintenance and power costs as a result of the lower machine speeds associated with higher substances. Thus to represent cost per ton a modification has to be made to the shape of the production/substance curve in Fig. 6.6 in such a way that the slopes in ABC and to a lesser extent in DE are accentuated. Variable costs per ton can be expected, to a first approximation, to remain relatively unchanged unless furnish mix alters. Taking these points into account, the probable relationship between cost per ton and substance is shown in Fig. 6.7.

The relative importance of the increased costs associated with substances at the ends of the making range depends entirely on the relation between the fixed and variable costs. Nonetheless, it is evident that outside the range
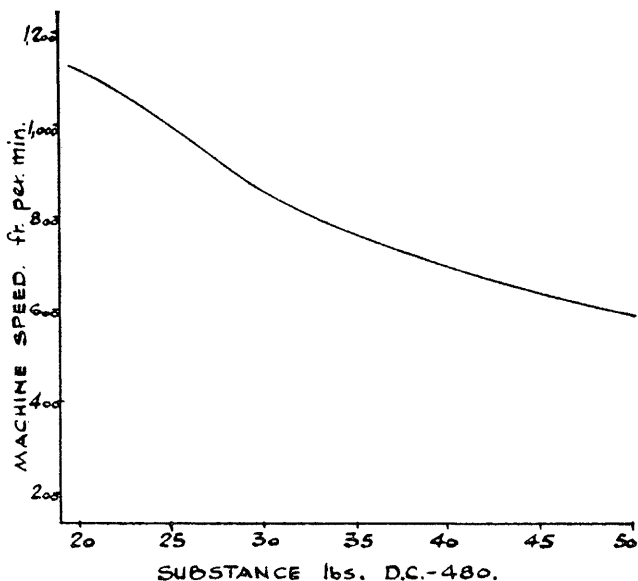
Fig. 6.4. Theoretical limitation imposed on machine speed by drying capacity (after Chedzey)

of substances where the curve forms a relative plateau of costs in CD, operation of the machine is less economical. This is particularly prominent at the lower end of the substance scale where speed is limited by couch draw and the drive, but applies also at higher substances once the region is reached where drying capacity controls the speed. Above all, the profitability of running low substances requires careful attention. Just how far this curve can be considered relevant to the majority of paper machines is difficult to say, but it seems likely that a fair plateau of costs such as that in CD does exist in some form on most machines, and awareness of the substance range it covers would indicate where sales should be concentrated.

6B.3 2 Machine conditions at different speeds

It is commonly believed, by papermakers if not by accountants, that the faster a machine is run and the higher the production, the more profitable is the whole operation. This is in fact a complete if excusable fallacy, and this final section will be devoted to explaining just why this is so.

The best way to illustrate this is by giving an example, and for this purpose it is proposed to use as a basis the machine for which cost figures were given on page 593. In that example, the basic conditions provided
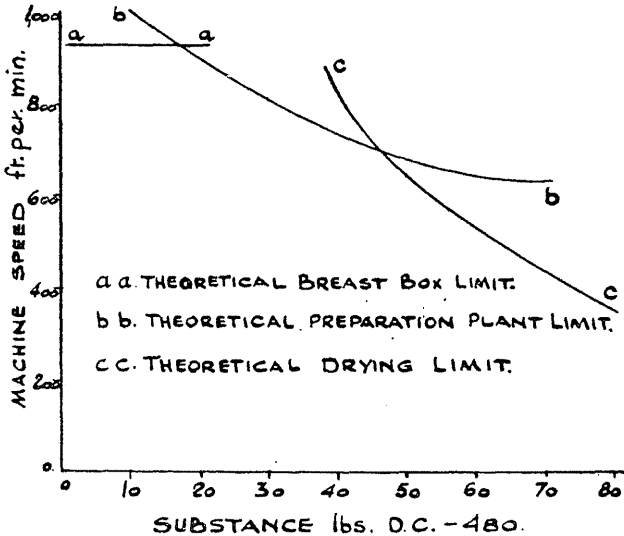
Fig. 6.5. Theoretical limitations imposed on machine speed by different restrictions (after Chedzey)

for an output of two tons per hour saleable paper with an average of 10 hours a week downtime. The standard costs worked out at £90 per ton for manufacturing, leaving £10 profit to make up the selling price of £100 per ton. Of the manufacturing costs, £4 per ton was due to machine maintenance, repairs, and clothing changes, and £3 per ton came from coal costs for power and steam, making a total of £7 per ton for items which (as discussed below) can be regarded as dependent on machine speed.

It will be supposed that these conditions refer to a machine speed in the region of 1,200 feet per minute and for the purpose of the exercise the relative conditions pertaining to a speed range from 1,000 to 1,250 feet per minute will be investigated. The graphs that follow are of course purely hypothetical but are nonetheless based on typical machine conditions with allowances made for effects that are likely to influence the results.

Firstly, Fig. 6.8 shows how, other things being equal, downtime increases with machine speed. It is a familiar phenomenon that at higher speeds

breaks occur more frequently and it becomes more difficult to feed straight through after a break. This is of course a feature of most pieces of machinery, the harder they are pushed the more often breakdown occurs. Such seems particularly to be the case when a paper machine has been run for many years at one speed and then an attempt is made to run faster. In such circumstances even a small increase beyond the familiar speed can often be sufficient to cause bearings to overheat, felts to come over the side, journals to fracture, gear wheels to split, and so on. But even when a range of speeds is commonly run to cope with a variety of grades, it is usual for
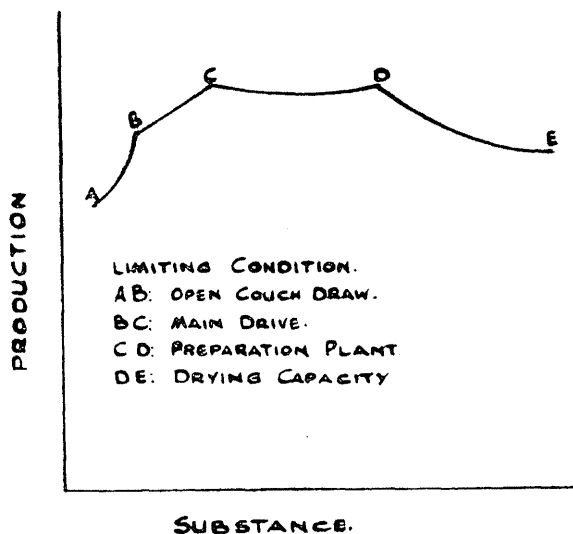
Fig. 6.6. Graph illustrating how machine production could be limited by different operating conditions

there to be a small but steady rise in downtime as speed is increased, followed at some point by a rapidly increasing downtime as speeds approaching the limit of the machine capability are reached.

The effect of increasing downtime at higher machine speeds is to reduce the rate of increase in production. In addition it is to be expected that difficulties will appear in maintaining uniform quality, for instance because at higher speeds there will be wider fluctuations in the drive output. Variation in quality results in an increasing broke percentage and this is a further factor reducing the rate of increase in production. The relation between production and machine speed might well therefore appear as in Fig. 6.9, showing a marked drop in the rate of rise towards the upper limit of the speed.

It can indeed happen that a point is reached where increases in machine speed are achieved at such cost in additional downtime and broke that total production actually begins to decline. Should this occur it is obvious that
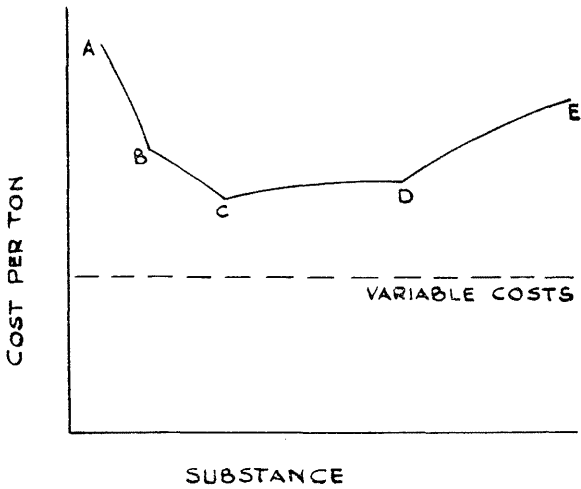
Fig. 6.7. Graph illustrating changes with substance in cost per ton of paper, based on production curve in Fig. 6.6
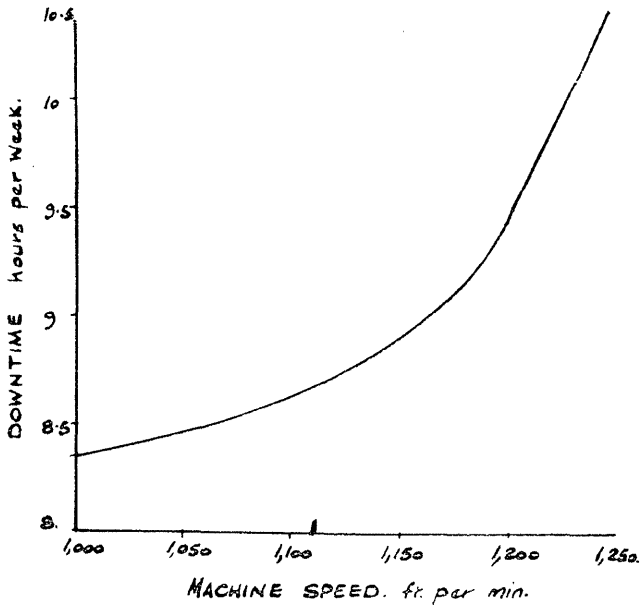
Fig. 6.8. Relation between downtime and machine speed

607

running at speeds beyond the point of maximum production is of no value. But apart from this, it can in fact be shown that for achieving optimum profit it is in all likelihood necessary to run at a lower speed than the one which gives maximum production.

This appears when account is taken of a further effect of running at higher speeds. It is invariably the case that the cost per ton of paper of such items as machine maintenance and repairs, clothing, and the cost of steam and power all rise as speed is increased. There are several reasons for this. Increased maintenance and repairs is a direct consequence of greater
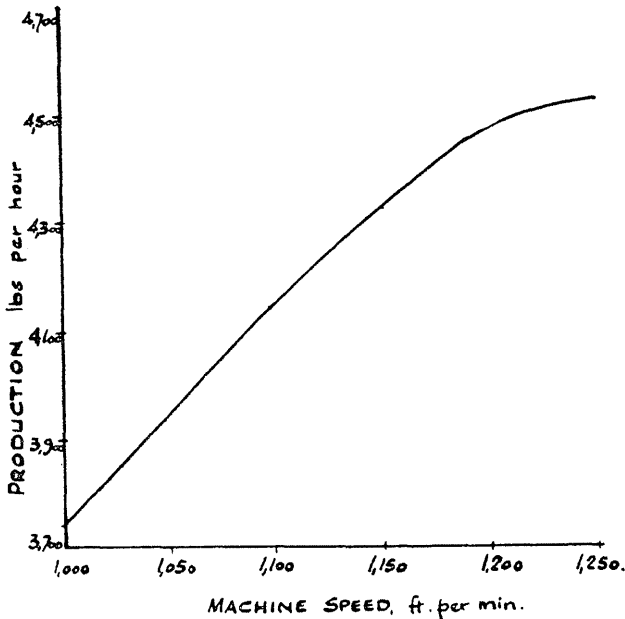
Fig. 6.9. Relation between production and machine speed

downtime. Increased clothing costs occur because wear is relatively faster at higher speeds and stronger more expensive felts may be needed; also a sudden failure which necessitates an unscheduled shut becomes more likely. A rise in steam consumption per ton of paper derives from the greater heat loss associated with the higher steam temperatures necessary to achieve the required drying rate. At the same time it is more than likely that dryness of the web entering the cylinders gradually drops, and it becomes necessary to dry the paper down to a lower moisture at the reel-up to counteract a less uniform cross-web profile, both of which lead to further increases in steam usage. Power demand can also rise faster than machine speed due to such factors as the higher head needed at the mixing pump and greater heat loss from bearings, which in turn means a rise in the cost of power per ton of paper produced. The relation between the machine

608

speed and the cumulative cost per ton of these particular items is shown in Fig. 6.10. In addition, the cost per ton at higher speeds may well increase due to the need for greater strength of the wet web, this being provided only by a more expensive furnish mix and heavier beating.

The net effect on the total profit at each machine speed is shown in Fig. 6.11. This has been calculated by taking the production in tons per hour multiplied by the difference between selling price and variable costs, then subtracting the fixed costs per hour. For example, at 1,100 feet per minute production is 4,150 lbs. per hour and cost of steam power, etc., is £5·8 per ton, making variable costs £66·8 per ton (see cost figures on page 593). Thus, profit is £(4,150/2,240) × (100 − 66·8) − 44 or £17·5 per hour. It is clear that an optimum speed exists at which profit is greatest. This
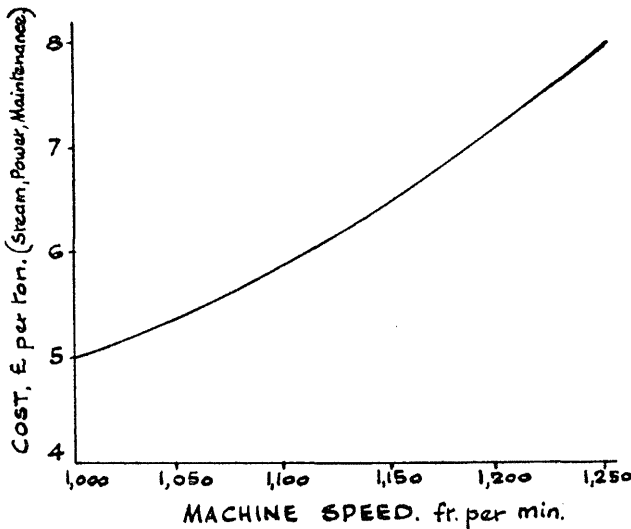
Fig. 6.10. Relation between machine speed and cost per ton for steam, power, clothing and maintenance

point, in the example at a speed of about 1,200 feet per minute, is clearly not coincident with the speed at which maximum production is obtained. This may well seem surprising, but is purely a consequence of the fact that the profit per ton diminishes at greater speed levels and this, associated with a growing decline in the rate of rise of production at the higher levels of machine speed, is sufficient to bring about the downturn in total profit.

The calculation of total profit, as opposed simply to total production or profit per ton, is essential for producing a correct analysis of the effect of different machine conditions. This point must always be borne in mind, particularly when comparing performance at different machine speeds. A good example of the ease with which it is possible to fall into error in this matter is due to Holt (5) and is illustrated in Fig. 6.12. The curve ACDB in this figure represents a hypothetical relation between the operating costs and

production, so that the swing upwards reflects the rising costs associated with higher production levels. The upper curve shows the cost per ton of paper derived from curve ACDB and this has a minimum at the point P. The production level at P is associated with point C on the production/cost curve in such a way that OC is a tangent to the curve (total cost divided by production is then a minimum). This point does not, however, indicate where profit is greatest.

To find the production giving maximum profit it is necessary to draw a line OAB representing the value of the paper produced. The total value is based on the selling price and has a straight line relationship with the
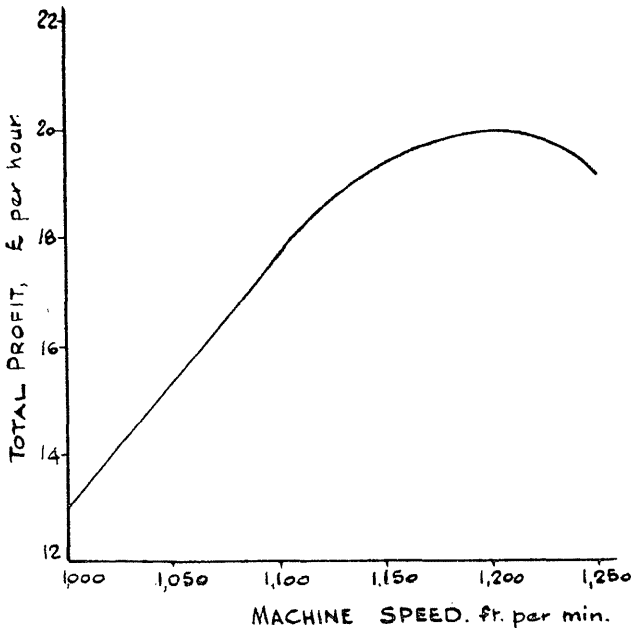
Fig. 6.11. Relation between machine speed and total profit

tonnage produced. Points A and B on the production curve define the region in which a profit can be made; production levels below A or above C result in an overall loss. The point of maximum profit is reached when the difference between the operating cost and the value is greatest, i.e. at point D when the tangent to the curve ACDB is parallel to OAB. Point D is always at a higher production level than C where cost per ton is least, the difference between the two being greater the higher the selling price and the more curved the relation between production and operating cost.

The dependence of overall profit on the selling price in this example is particularly important to note. It is evident from the graph that the lower the selling price (and hence the less the gradient of OAB) the lower is the production level leading to maximum profit. Once the production/cost

curve has been identified for different grades of paper run on a machine, it will be clear that those grades carrying a lower profit margin per ton will yield maximum profit when run at lower production levels. This is contrary to popular belief that the lower the profit margin the greater the production needs to be to make operation worthwhile. Such is the case only if production levels of all grades are relatively low and fall in the region AC. If a machine is consistently run close to point D for one particularly common
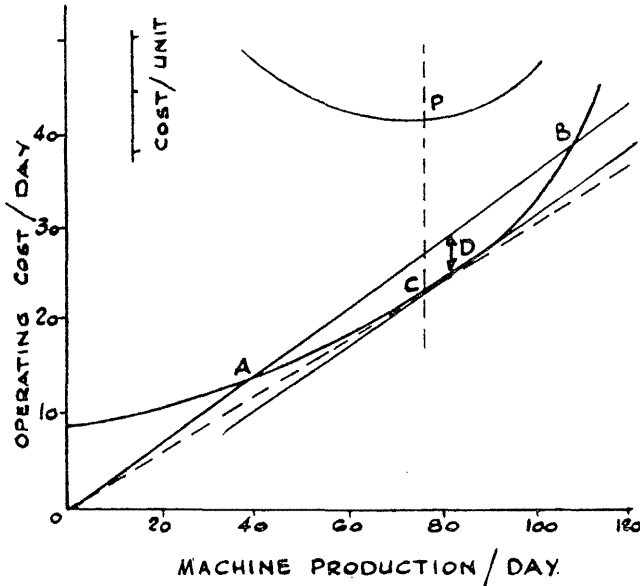
Fig. 6.12. Relation between operating costs and production (after Holt)

grade, and it is then proposed to produce another similar grade at a lower selling price, then maximum return is clearly provided at a lower production level.

There is, fortunately, a final point of consideration for the papermaker who may now begin to worry about matters that formerly seemed straightforward. The examples just presented have been chosen to highlight little-known effects. In practice it is unlikely that on most machines the point of greatest profit is very precisely defined. Conditions can change so rapidly that it often cannot be possible to locate the position with any degree of accuracy. Equally important is the sensitivity of the machine system to small changes in speed. In Fig. 6.11 it is evident that profit does not alter significantly through a range of almost 60 ft. per minute, i.e. from around 1,170 to 1,230 ft. per minute. If the profit/speed curve were flatter, this range would be much wider and precise location of the optimum speed becomes far less critical.

Nonetheless such a curve as that shown in Fig. 6.11, or its alternative

611

relating production to total operating costs, should ideally be derived for the major grades run on any machine. For its very shape is useful to know as this should affect how the machine is run. For instance, if there is no pronounced peak in the profit/speed curve, obviously there is no particular merit in running at the higher end of the speed range as opposed to the lower end, if only because over a long period greater wear and tear on the machine at the higher speed will begin to tell.

If running conditions indicate that the normal speed falls in the early part of the curve where profit increases with rising speed and production, then different considerations have to be taken into account. When a machine has a limited order book, it could well in such circumstances pay to run as fast as possible and then shut for a longer period. This state of affairs is, however, not very desirable because it leads to an unstable business: when orders are plentiful high profits can be accumulated, but when they are limited profit is low. It is preferable that operation normally falls in the region where quite large changes in speed and production do little to affect the overall profit. When this is the case, it is possible for the mill to tolerate appreciable swings in demand without feeling the pinch. And this, after all, is most important to the peace of mind of the paper-maker.

REFERENCES

(1) Chedzey, C. S.: 'Standard Outputs of Fourdrinier Machines.' Proc. Tech. Sec. 37, 3, 439. December, 1956.
(2) Hendry, I. F.: 'The Calculation of Quality Control Limits.' Paper Maker. International number, p. 46. 1959.
(3) Muhonen, E. J.: 'The Principles of Loss Calculation in the Paper Industry.' Paperi ja Puu. 41, 3, 97. March, 1959.
(4) Anon: 'Standard Costs in a Paperboard Mill.' Paper Maker and Paper Selling 80, 5–6, 7. 1961.
(5) Holt, S. G.: 'A Method of Economic Analysis of the Papermaking Process.' TAPPI 44, 5, 325. May, 1961.
(6) Turner, C. O. and Filleul, H. W.: 'Reporting on Paper Machine Utilisation.' APPITA Proceedings 14, 4, 15. January, 1961.
(7) Williamson, F.: 'Mill Management and Costing.' World's Paper Trade Review 155, 16, 1423. April 20; p. 1643, May 4; p. 1837, May 18; p. 2045, June 1; p. 2247, June 15; p. 2419, June 29, 1961.
(8) Gaudet, E. J.: 'Better Control of Broke and Downtime Costs.' Paper Trade Journal 146, 43, 26. October 22, 1962.
(9) Mardon, J.: 'The Technical Audit Principles: Promulgation and Practice.' Paperi ja Puu 45, 12, 689. December 31, 1963; 46, 4, 305. April 30, 1964; 46, 6–7, 403. July 15, 1964.
(10) Barbour, D. R., and Tweedie, J.: 'Economical Design Considerations for Paper-machines and their Alteration.' Paper Technology 5, 4, 377. August, 1964.
(11) Nuttall, G. H. and Ainge, D. S.: 'Quality Control: correcting a property outside limits.' Paper Technology 5, 2, 121. April, 1964.
(12) Stevens, J. Jr. and Newell, S. R.: 'Waste Control in a Fine Paper Mill.' TAPPI 47, 7, 157A. July, 1964.
(13) Wells, L. C.: 'Around the Mills. No. 2 Broke.' What We Are Doing: Bulletin of the B.P. & B.I.R.A., No. 37. December, 1964.
(14) Cummins, O. J.: 'Instrumental Approach to Evaluating Paper Machine Operation and Efficiency.' TAPPI 48, 8, 47A. August, 1965.
(15) Mardon, J. and Mardon, D. H.: 'The Techniques and Utility of Lost Time Analysis.' TAPPI 48, 10, 71A. October, 1965.
(16) Brauns, O.: 'Commercial and Economic Viewpoints on Quality Assurance in the Paper Industries.' Svensk Pap. 69, 14, 455. July 31, 1966.
(17) Cummins, O. J.: 'Automatic Monitoring can improve Paper Machine Efficiencies.' Paper Trade Journal 150, 42, 58. October 17, 1966.
(18) Harding, H. A.: 'The Development of Quality Control in Paper Mills.' Paper Maker. Part III: 151, 3, 73; Part IV: 151, 7, 85. March, July, 1966.

INDEX

615

Wire, mark   **3A.25; 3B.11; 3B.51; 3B.74**
— return rolls   **3B.64; 3B.72; 3B.73; 3B.10 1**
— slope of   **3B.75**
— tension   **3B.10 2; 3C.11**
— — effect on life of   **3B.71; 3B.72**
— — effect on table roll disturbances of   **3A.11; 3B.11; 3B.12**

Yankee cylinder   *see*   Cylinder, M.G.

THEORY AND OPERATION OF THE
FOURDRINIER PAPER MACHINE

by Geoffrey H. Nuttall

This work is intended primarily for persons who are, or will be, directly associated with the production of paper or with technical aspects of papermaking. It assumes some basic knowledge and a fair degree of familiarity with paper machines, and the aim is to provide a comprehensive background of information which can be continually referred to but is at the same time sufficiently readable to be suitable as a text book for gaining advanced knowledge of the process. In scope it fills the gap between general books on papermaking which give a broad introduction to the subject, and the large reference works which are mainly concerned with giving a comprehensive description of all equipment and techniques in use. Students following higher courses in Paper Technology will find that the material is presented at the right level for their needs. Pulp suppliers, paper machine equipment manufacturers, and paper users will find this book an invaluable source of reference.

The Divisions and sub-divisions of the Work

The work is divided into six parts dealing, respectively, with the Wet-end Flow System, Screens and Cleaners, the Wire part, the Press Section, Dryers and Calenders, and Production Control Methods. All except the last part are divided into three main sections. The first section describes theoretical aspects of the process at a level which can be understood by anyone possessing a basic knowledge of physics; it is essentially descriptive rather than analytical and is intended to give a general background of the fundamental principles so far as they are known.

The second section deals with operational aspects and details the various factors which can affect and upset the process. Particularly in this section the results of experimental work have been freely drawn on. The intention is to place in perspective the influence of operational variables associated with running the paper machine in order to indicate how best different quality requirements can be fulfilled and the whole operation brought under more systematic control.

The third section is concerned essentially with practical aspects of paper machine operation. The value and use of process instrumentation is discussed, maintenance requirements are detailed, and the main tasks of machine crews with particular emphasis on the problems of running the machine to produce a consistent product are described. There is also some discussion of the basic practical tasks involved in machine operation.

Previously unpublished material on Production Control Methods

The final part of the work, concerned with Production Control Methods, outlines the data relating to machine operation that are essential if adequate financial control is to be achieved. The regulation of speed, downtime, broke and so forth to reduce operating costs, and ways of comparing the economics of producing different grades on a machine are described. This section includes much new material hitherto unpublished.

The work has been serialised in 'The Paper Maker', London, during the years 1962-1967. The articles have been completely revised and brought up to date for publication in book form. The text-book runs to approximately 250,000 words with over 100 line illustrations. A comprehensive index and reference list is included.