ECONOMICS

OF A

SEWAGE TREATMENT POWER PLANT

THESIS

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Vita

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Shortly after graduation, I was employed by Todd Shipyards Corporation-Combustion Equipment Division. I was engaged chiefly in research and development work on oil burners at the U.S.Naval Boiler and Turbine Laboratory in Philadelphia, Pa.

I accepted a position with the Department of Public Works of the City of New York-Bureau of Sewage Disposal Design, in July 1950. I have been employed since April 1951 at the Material Laboratory of the New York Naval Shipyard in the Engine Vibration and Dynamics Section.

Information and data for the subject matter was first compiled in November, 1950. The writing of this thesis commenced shortly after receiving approval of the subject matter from Professor E.L.Midgette in January, 1951.

Acknowledgement

The author wishes to express his sincere appreciation to Professor M. J. Steinberg for his timely criticisms and suggestions, and general guidance in the formulation of this thesis.

The author also wishes to acknowledge the devoted assistance of his Mother in the preparation of the manuscript.

Synopsis

The purpose in offering the subject "Economics of a Sewage Treatment Power Plant" is to present an analysis of the economic considerations involved in the selection of the source or sources of power. The plant considered may generate all or part of its power requirements or operate entirely on purchased electricity. The additional investment required for an engine installation must be justified by a sufficient saving, if any, in annual costs.

Engines and auxiliaries used in sewage treatment plants are discussed in detail and various operating data is presented. The relationship of heating requirements to plant design for the above three projects is investigated.

It is determined that, for the plant considered, purchasing all power requirements is the least expensive of the three schemes. It must be recognized, however, that the studies made are valid only for the particular conditions considered. Since conditions vary depending upon the location, a similar analysis made with other considerations might yield a different result.

It is the intent of this thesis to present sufficient applied design procedure to enable the reader with an engineering background to prepare a similar study for proposed sewage treatment plants.

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1. Introduction

A sewage treatment plant includes an installation of sewage pumps and air blowers necessary for the secondary treatment of the sewage by the activated sludge process, as well as miscellaneous auxiliary equipment. The above units may be operated either electrically or by direct-connected engines, as we may install digestion tanks and collect sludge gas. It will not be possible to obtain sufficient power from the sludge gas alone to continually operate all the equipment, even with reasonable gas storage facilities. Therefore, it will be necessary to obtain supplemental power from other sources.

The purpose of this study is to determine the economies of several types of prime movers for the various services, as well as of the various sources of supplemental power.

In some municipalities, the choice of power may be dictated by other than engineering considerations. Purchased electric power or diesel oil generator plants are the only possibilities where sludge is not digested and sludge gas is not available. Digestion of the sludge will reduce considerably the volume to be handled and will eliminate offensive odors emitted by non-digestion plants. The decision will, however, be based on comparative studies of a number of alternate schemes. In general, there are three types of installations which are to be considered:

1) All power derived from dual fuel engine-driven generators using available sludge gas supplemented with purchased oil. All equipment to be motor operated on generated current with no utility company connection.

2) Some major items of equipment, such as blowers or main pumps, or both, direct driven by gas engines; purchased electricity for load which cannot be handled by the gas engines and for plant lighting.

3) All equipment operated on purchased electric power; no engines. Sludge gas to be used only for space and digestion tank heating with deficiency, if any, made up by purchased fuel - gas, oil, or coal.

In making an economic study of the power plant, we must include both capital charges, or costs incidental to the investment of money, and annual operating costs. Capital investment includes the costs of the following:

Substructure and superstructure of buildings required for each scheme.

Engine driven blowers, or Motor driven blowers.

Motor driven pumps, or Engine driven pumps.

Engine generators

Electrical work and equipment

Heating plant.

From the total investment, the annual fixed charges are derived after establishing an estimated life for amortization and interest charges.

Amortization of equipment will be based on 20 years at 3½%, and structures 40 years at 3½%, using sinking fund depreciation. The sewage treatment plant is a municipal project, and as such, is exempted from property and income taxes. In paying for public improvements by general taxation the money is taken from municipal funds which have been apportioned for each separate purpose by the legislative department of the government. Annual insurance charges will be taken at 1% of the initial investment.

The annual costs will include the fixed charges, cost of purchased electric power, oil and gas for power and heat, labor, and maintenance or repairs.

Particular attention should be given to the basic assumptions, since any scheme can be unfairly rated by weighing certain data. For example, the capital cost of structures and equipment will be much greater for plants generating their own power. The study would favor purchased electricity if we used a very short life for amortization purposes. The same effect would also be obtained by too low an estimate of available gas. On the other hand, generated power can be favored by assuming that utility companies will insist on high breakdown service charges by the apportionment of loads between generated and purchased electricity. Generated power would also be favored by too high an estimate of gas production.

A. Essential Elements of an Activated Sludge Sewage Treatment Plant

The essential elements of the plant are bar screens, grit chambers, sewage pumps, aeration tanks, settling tanks, sludge digesters, dual-fuel engine generators, and blowers.

1) Bar Screens are a primary element in any sewage disposal system. Normally, these units are the first piece of mechanical equipment which the raw sewage contacts. Here it is that the large items, such as sticks, branches, boxes, and even newspapers, which make their way into the sewer mains, are screened out. Rising rows of teeth on a chain drive lift these pieces from the flowing sewage to where they can be hauled away or further processed. The primary bar racks remove objects greater than three inches and the secondary bar racks one inch particles.

2) Grit Chambers serve to remove the finer inorganic materials from the sewage. Here it is that sand and small refuse from roads is removed, leaving the raw sewage primarily in an organic state. The grit, itself, is collected and used for earth fill or other purposes. Raw sewage is pumped to further processing points. Grit washers clean the grit sediment prior to disposal. Grit chambers control the velocity of flow of the sewage by critical depth weirs so as to remove 90% of sand that is coarser than 60 mesh.

3) Pumps lift the sewage to higher levels for further processing. These pumps are necessary wherever the treatment plant is above or on a level with arterial sewer lines.

4) Aeration Tanks supply the bacteria naturally present within the sewage with a plentiful supply of oxygen. Without it, the bacteria would not reproduce and remain in the healthful condition necessary for breakdown of organic solids. Power for the blowers and main sewage pumps is the major load on the plant.

5) Settling Tanks permit solid matter within the sewage to settle to the bottom while liquid flows off for disposal in a moving stream. Settled matter goes to the sludge digestion tanks after thickening.

6) Sludge Digesters- Sludge from the settling tanks is heated and bacterial action generates combustible gas little different from that employed for domestic and industrial use.

7) Dual-Fuel Engine Generators, in plants generating their own power, are fueled by gases from the sludge digestion tanks supplemented by diesel oil in such quantities as may be necessary.

8) Blowers, powered by generated electricity supply air to the

aeration tanks and for other uses within the station. This is the primary demand for electric power within the treatment plant.

The elements of a conventional activated sludge sewage treatment plant are presented in figure 1.

Sewage treatment plants remove the putrescible matter from the liquid carrying it by settling and by scraping devices called collectors, which transport the sediment, or sludge, to the suction lines of sludge pumps from where it moves on to further processing.

The settling is made very effective and complete by first subjecting the sewage to aeration, in which air is released at the bottom of deep tanks in very fine bubbles. The activated sludge process uses between 0.3 and 0.8 cubic feet of air per gallon of sewage and the value of 0.5 cubic feet will be adopted.

The settled material, or sludge, presents a disposal problem since it is mostly water, varying from a low of about twelve pounds of water per pound of solids, to as high as 98% in some processes.

However, the techniques of sludge digestion were developed early in the twentieth century. In the present improved form of digestion, the sludge is warmed to 87 or 90 degrees Fahrenheit, and, in the absence of air, a rapid bacterial action sets in, first destroying the softer solids, the most troublesome and bulky part.

Sludge digestion gives off a copious supply of methane. It is mixed with considerable inert carbon dioxide, but the fuel value of the mixture of about 650 B.T.U. per cubic foot which is higher than the usual manufactured gas. The digestion process is favored by temperatures near 90 degrees Fahrenheit, so heat is required, especially in the winter.

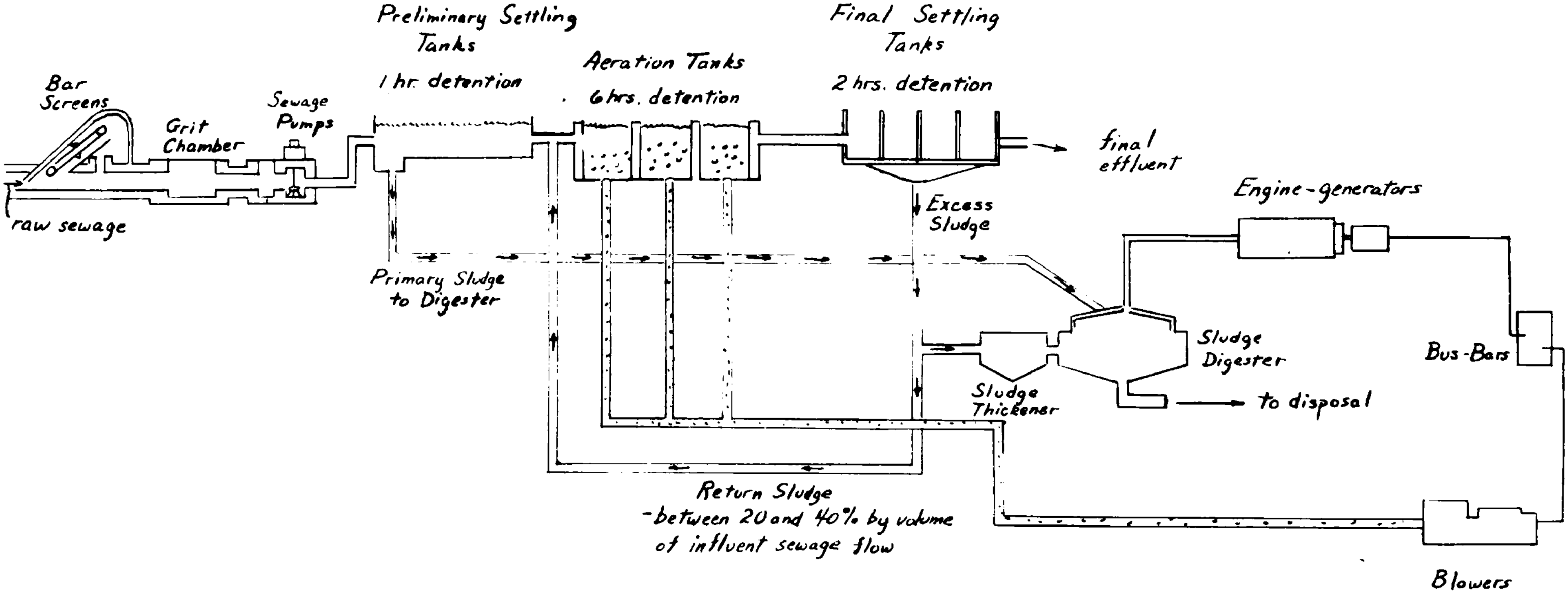


Figure 1

CONVENTIONAL ACTIVATED SLUDGE SEWAGE TREATMENT PLANT

-90% removal of suspended solids and biochemical oxygen demand of sewage.

When the process is completed, which takes normally 30 to 60 days, during which water is gradually removed, the sludge has decreased in volume and has lost all traces of its sewage origin, becoming much like a black swamp muck of thin liquid consistency. The digested sludge is valuable for land-fill, fertilizer filler and soil improvement. Sludge that cannot be used for these purposes may be disposed of by barges at sea, or may be insinerated after drying. Because of the obvious economic and operating advantages, practically all new sewage plants include digestion of sludge and heating of sludge with the gas produced.

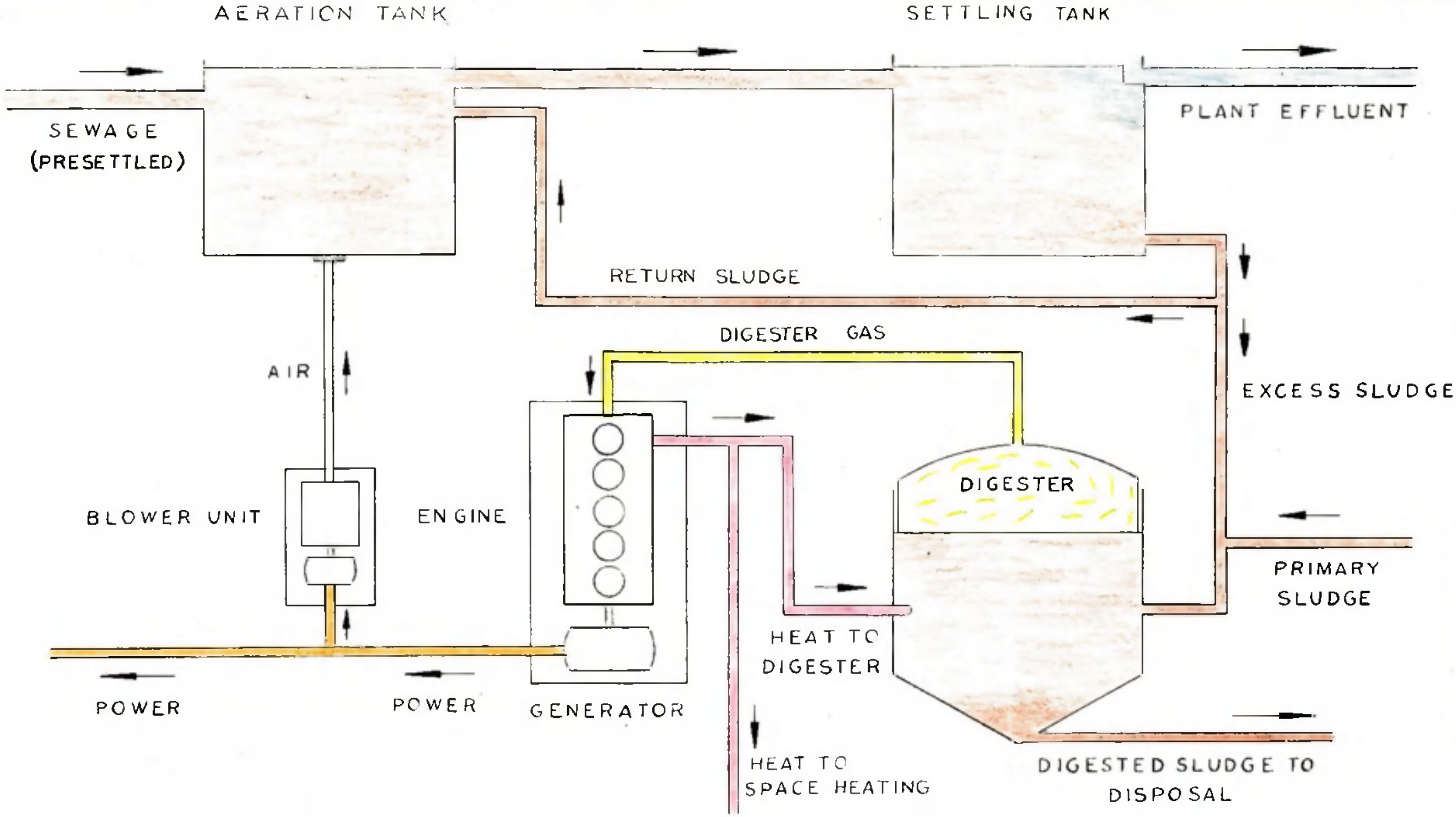


Figure No. 2

HEAT AND POWER FROM SLUDGE

B. Power Production from Sewage

The most efficient engine rejects to the jacket water and exhaust most of the heat put into it, converting about 35% of the fuel value of the gas into power. The rest goes to the cooling water and to exhaust, and most of it can be recaptured for heating purposes.

The production of power from sewage is, in effect, a by-product of the combustion of the sludge gas, the latter, itself, a by-product of the digestion process. Fig. 2, page 18 illustrates the heat and power production cycle for a plant generating its power requirements.

In practice, the supply of gas will normally be steady and reliable. However, some equalizing storage in large plants may be desirable to bridge the daily fluctuations in sewage flow. The waste heat of the engines is transferred back to the digesters. In this way up to 80% of the heat value of the sludge gas may be utilized.

Sewage treatment plants can be rated in kw.-hrs. used per million gallons treated. In terms of population, a flow of one million gallons per day represents about 7000 persons. This rating varies with both the completeness of the process and the pumping required. About 625 to 850 kw.-hrs. per million gallons are required depending primarily upon the amount of aeration given the sewage and the pumping head. The cost of treating sewage, exclusive of fixed charges, is $15. to $20. per million gallons, so power cost is a major item ranging, at one cent per kw.-hr., from $6.25 to $8.50.

With great certainty 1.0 to 1.2 cubic feet of sludge gas per day per capita of population may be expected. Per million gallons of sewage, this gives 7000 to 8000 cubic feet of gas, which in the latest engines can give a kilowatt-hour per 15 cubic feet, or, allowing for losses, about 500 kilowatt-hours per million gallons. This is from 55% to 85% of the energy requirements in different plants of this type.

Therefore, for each million gallons of sewage per day (m.g.d.) treated, in a year, (365 x 500) or 180,000 kw.-hrs. can be generated, for which about 40 kw. of plant equipment is required. This represents additional investment at $200 per kw. in the plant of $8,000 per m.g.d. capacity.

Against this, is conservatively charged eight per cent, or $640. per year, equal to 3.5 mils per kw.-hr. which, plus the cost of running the power plant, make up the cost of power.

The annual power cost with Consolidated Edison Co. of New York's Service Classification No. 3, is about $2,000 per m.g.d. Against this are carrying charges on about 40 kw. of power plant, $640, so there is about $1,360 left for a year's operation, maintenance or repairs, plus saving.

It is therefore, to be decided for a given size plant whether there is an economic justification for utilization of gas power. Design skill may be needed to assure continuity of operation and to get adequate return from plant investment. However, it is to be seen whether the larger investment necessary for self-generation will be compensated by a sufficient saving, if any, in annual costs, over a plant of the same capacity purchasing all or part of its power requirements.

C. Factors Affecting Sewage Treatment Plant Design

In the planning and design of mechanically equipped sewage treatment plants, some features require special attention, rather different from the common run of industrial, public utility, or even other public works.

Up to a couple of decades ago, power and moving machinery seemed out of place in the sewage system—unreliable, troublesome and, finally, a mess of rust to be removed with difficulty.

The necessity of making sewage flow up-hill has led to numerous other demands for power-driven equipment to make the system more efficient, more compact and less costly (for its performance, of not per m.g.d.).

The large plant today has all the elements, and presents all the problems of the industrial process plant, with special requirements, characteristics and problems arising from its size, nature and public service status.

Features peculiar to the sewage treatment plant which affect planning are:

(a) The requirements for high reliability in continuous non-stop operation.
Make repair or replacement inexpensive and possible without shutdown.

(b) The peculiar humidity, gas, dirt and flood conditions.

(c) Insure permanence of equipment and avoid repair expense.

(d) Facilitate inspection and test, and relieve load on operating force, and

(e) Also to be considered, is the usual method of budgetary control of a municipal public plant in which immediate economy has complete power of veto, no matter what the cost.

11. Plant Sewage Flows

A. Population Data for Area Served

The sewage plant under study is intended to serve an area which is used as a summer resort. The winter, or permanent population will be assumed to be 40,000 and the summer population 90,000. A future winter population of 88,000 and summer population of 180,000 may be expected in 1970. The plant will discharge its effluent into a large river, which is not used by the community as a source of drinking or for bathing purposes for a sufficient distance downstream, so as to render the water safe after the sewage is treated by the conventional activated sludge process.

The plant sewage flows will now be considered in order to arrive at the design capacity. The summer and winter flows, minimum, average and maximum must be estimated.

Water consumption may be divided into four classes of users. These are: (1) domestic, (2) commercial and industrial, (3) public, (4) loss. The yearly average consumption in gallons per capita day (g.c.d.) may be expected to vary from a minimum of 40 to a maximum of 160, as reported by the National Lime Association survey in cities and towns where services are metered. The sewage flow for the permanent winter population will be taken as 100 g.c.d. for 1950, 110 g.c.d. for 1960, and 120 g.c.d. for 1970. For the additional summer population, the sewage flows will be taken as 95 g.c.d. for 1950, 100 g.c.d. for 1960, and 105 g.c.d. for 1970. The minimum, average, and maximum flows are now tabulated for both the winter and summer. A constant infiltration flow will be assumed in the winter as against a varying infiltration flow for the summer. It is necessary to recognize variations in sewage flow from the annual average in determining the capacities of pump and blower equipment. The flow of sewage can be considered to consist of water consumption due to permanent population, of groundwater infiltration, of water consumption due to temporary summer population (not including the permanent population) and of water consumption due to transients. Table 1, page 14, tabulates present and anticipated future sewage flows. Figure 3, page 15, illustrates the permanent winter population curve and figures 4 and 5, pages 16 and 17, present plant sewage flow versus years and time of year respectively.

Table No. 1

Plant Sewage Flows

	1950	1960	1970
Permanent Population:			
Winter	40,000	55,000	88,000
Summer	50,000	60,000	92,000
Gallons per Capita-day			
Winter	100	110	120
Summer.......	95	100	105

	Permanent Winter Flow-m.g.d.	Permanent Summer Flow-m.g.d.	Infiltration and Transients -m.g.d. Winter	Summer	Winter Flow	Summer Flow
1950						
Minimum	2	5	6	3	8	10
Average	4	5	6	6	10	15
Maximum	8	10	6	12	14	30
1960						
Minimum	3	6	8	4	11	13
Average	6	6	8	8	14	20
Maximum	12	12	8	16	20	40
1970						
Minimum	5.5	10	9	4.5	14.5	20
Average	11	10	9	9	20	30
Maximum	22	20	9	18	31	60

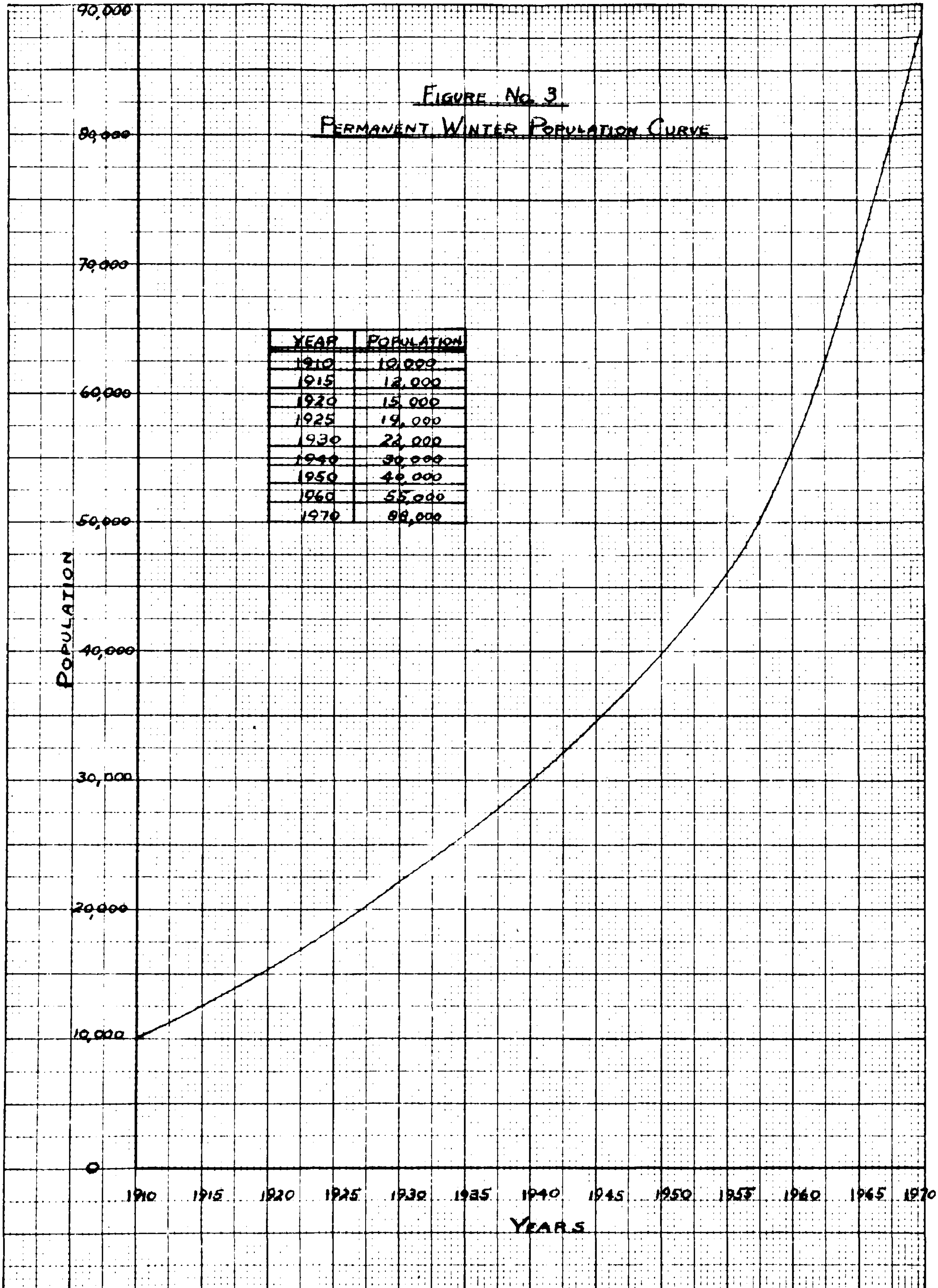


FIGURE No. 3
PERMANENT WINTER POPULATION CURVE
YEAR | POPULATION
1910 | 10,000
1915 | 12,000
1920 | 15,000
1925 | 19,000
1930 | 22,000
1940 | 30,000
1950 | 40,000
1960 | 55,000
1970 | 88,000
POPULATION
90,000
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
1910 1915 1920 1925 1930 1935 1940 1945 1950 1955 1960 1965 1970
YEARS

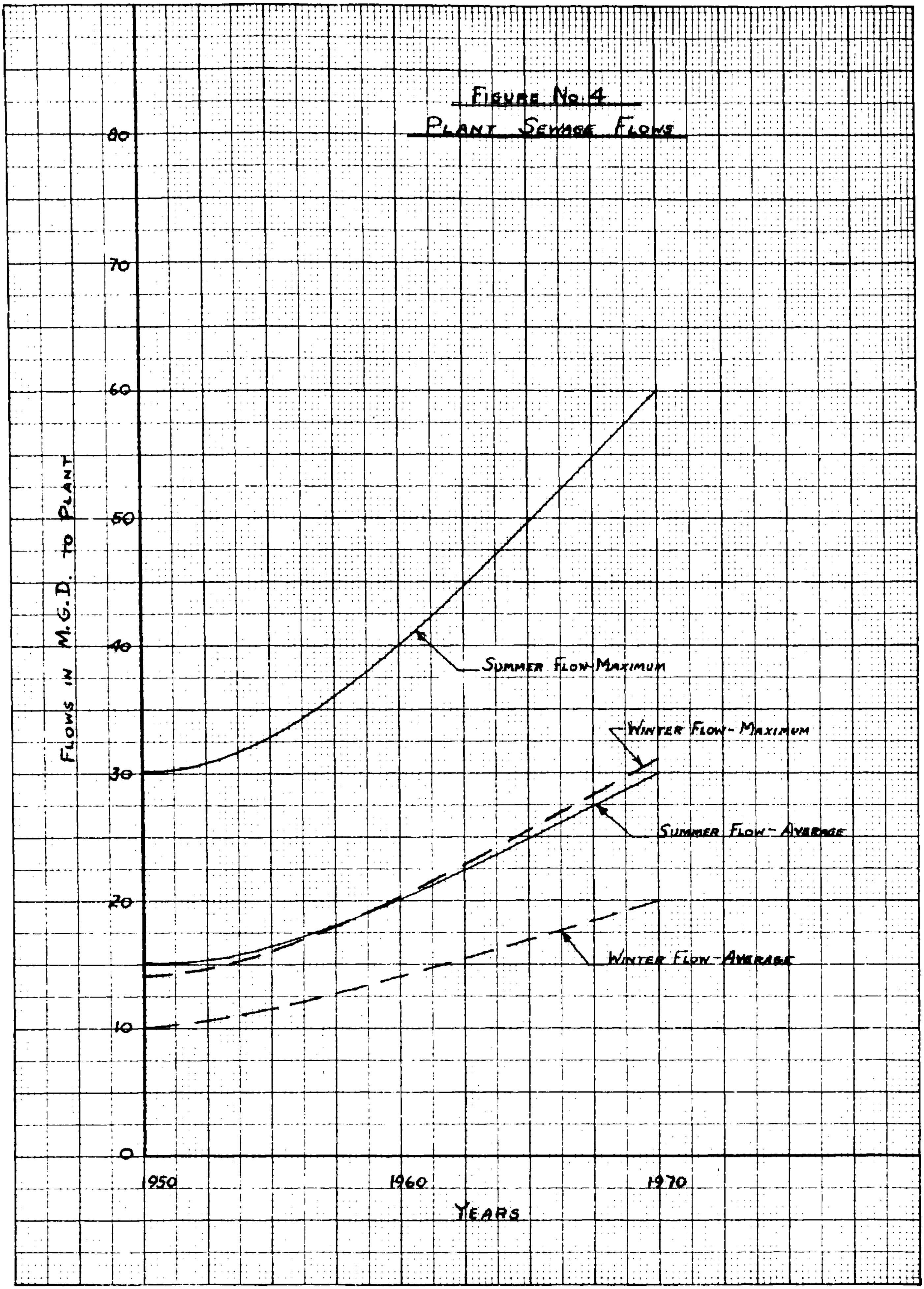


FIGURE No. 4
PLANT SEWAGE FLOWS
80
70
60
50
40
30
20
10
0
FLOWS IN M.G.D. TO PLANT
SUMMER FLOW-MAXIMUM
WINTER FLOW- MAXIMUM
SUMMER FLOW- AVERAGE
WINTER FLOW-AVERAGE
1950
1960
1970
YEARS

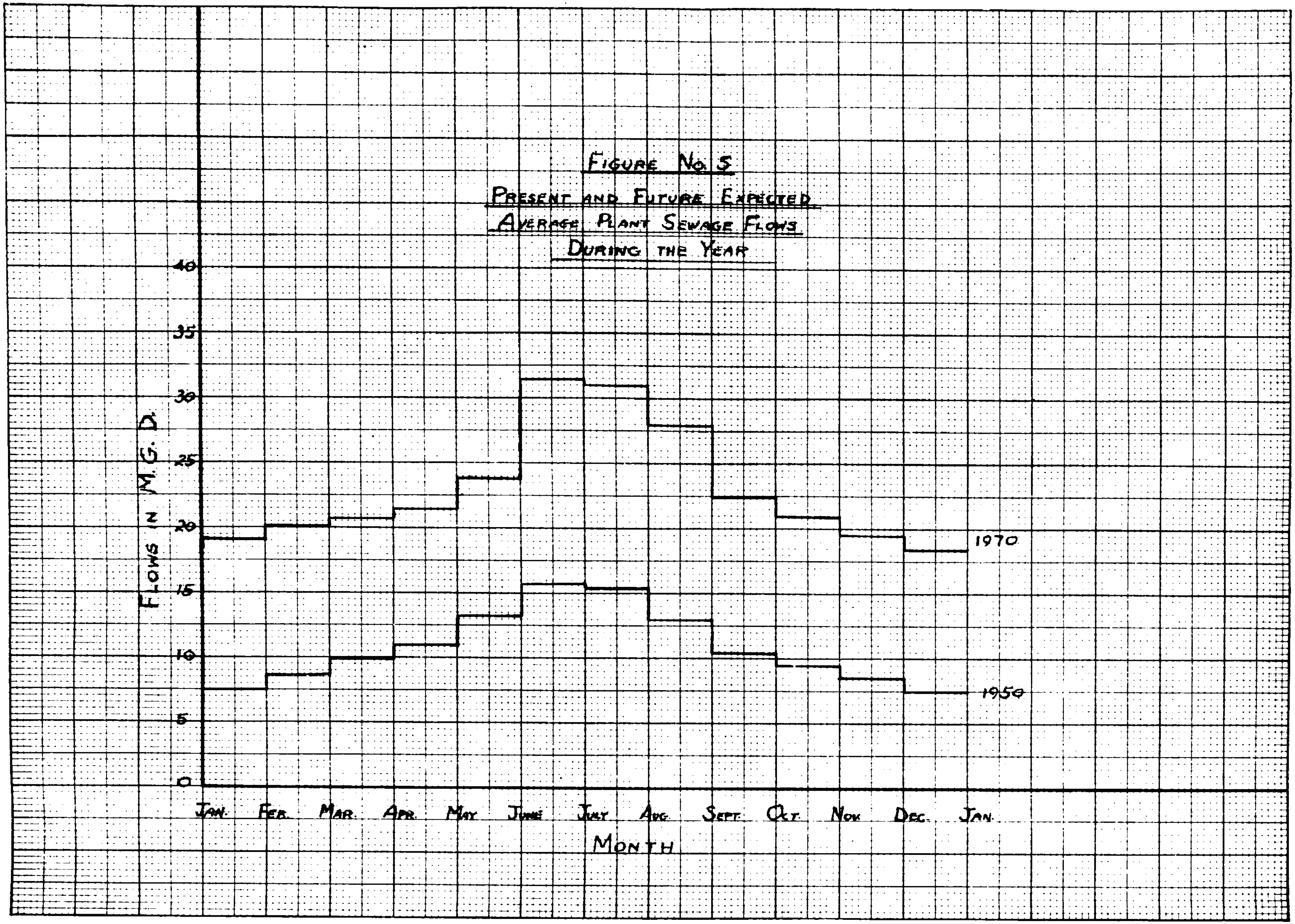


Figure No. 5
Present and Future Expected
Average Plant Sewage Flows
During the Year

B. Availability of Gas and Plant Power Requirements

An average air requirement and therefore blower delivery of 0.5 cubic feet of air per gallon of sewage will be adopted as discussed previously on page 5. The air pressure differential to be maintained at the blowers is taken as 7.0 pounds per square inch, which is the value maintained in New York City's sewage treatment plants. There will be some variations in pressure, depending upon the rates of air application and the condition of the diffusers. Cleaning operations performed on the diffusers will permit lower average pressures to be maintained.

Three, 3,000 c.f.m. rotary positive displacement blowers will be installed at present with an additional 2,000 c.f.m. blower to be provided for future operation. The calculations relating to the above selections are included in the appendix, section I.

The main sewage pump installations to be made at present are as follows: one 7.5 m.g.d., one 10 m.g.d., and two 15 m.g.d. An additional 15 m.g.d. pump will be installed in the future to conform with the expected plant sewage flow curves, figure 4, page 16. The sewage must be raised from low level sewers and pumped to the various treatment points within the plant. The total dynamic head will be taken as 35 feet. This value will be used in subsequent plant layouts and in the calculations in the appendix, section 1, relating to the pumping power requirements.

Auxiliary plant equipment includes sludge pumps, mechanism drives, major equipment auxiliaries, lighting, and other incidental equipment throughout the plant. The auxiliary load for the plant under consideration will be taken as 4 kw. per m.g.d. flow, which is the average of results from the Tallmans Island Sewage Treatment Works, New York City.

The sewage treatment plant power requirements are given in table 2, page 20 in which is shown the amount of gas required in cubic feet per hour. Figure 6, page 21 shows a graph of cubic feet of gas required per horsepower-hour vs. % load for a 300 H.P. dual fuel engine at the 26th Ward Sewage Treatment Works, New York City.

In the study of power costs for the sewage plant, there are, among the assumptions made, three in particular that are probably subject to variation. These are gas production per capita, air used per gallon of sewage, and air pressure for the aeration air.

Gas production for plants in operation is obtained from population data, which is somewhat indefinite. Three bases for the population data will be used:

1. The average flow divided by 130 gal./cap./day .
2. The average present flow divided by the design flow and multiplied by the design population.
3. Figures from various sources on estimated present populations for these plants.

Table No. 2

Plant Power Requirements

	Present (1950)		Future (1970)	
Minimum Flow	Winter	Summer	Winter	Summer
Pumping kw.	52	63	90	124
Blowers kw.	105	158	212	317
Auxiliaries kw.	40	60	80	120
Total kw.	197	281	382	561
Total H.P.	264	377	512	753
Gas required—cu.ft/hr.	2980	5000	5710	8450
Average Flow				
Pumping kw.	63	93	124	186
Blowers kw.	105	158	212	317
Auxiliaries kw.	40	60	80	120
Total kw.	208	311	416	623
Total H.P.	279	417	559	835
Gas Required—cu.ft./hr.	3050	5240	6110	9150
Maximum Flow				
Pumping kw.	87	186	192	388
Blowers kw.	105	158	212	317
Auxiliaries kw.	40	60	80	120
Total kw.	232	404	484	825
Total H.P.	311	541	649	1105
Gas required—cu.ft./hr.	4940	5950	7940	12140

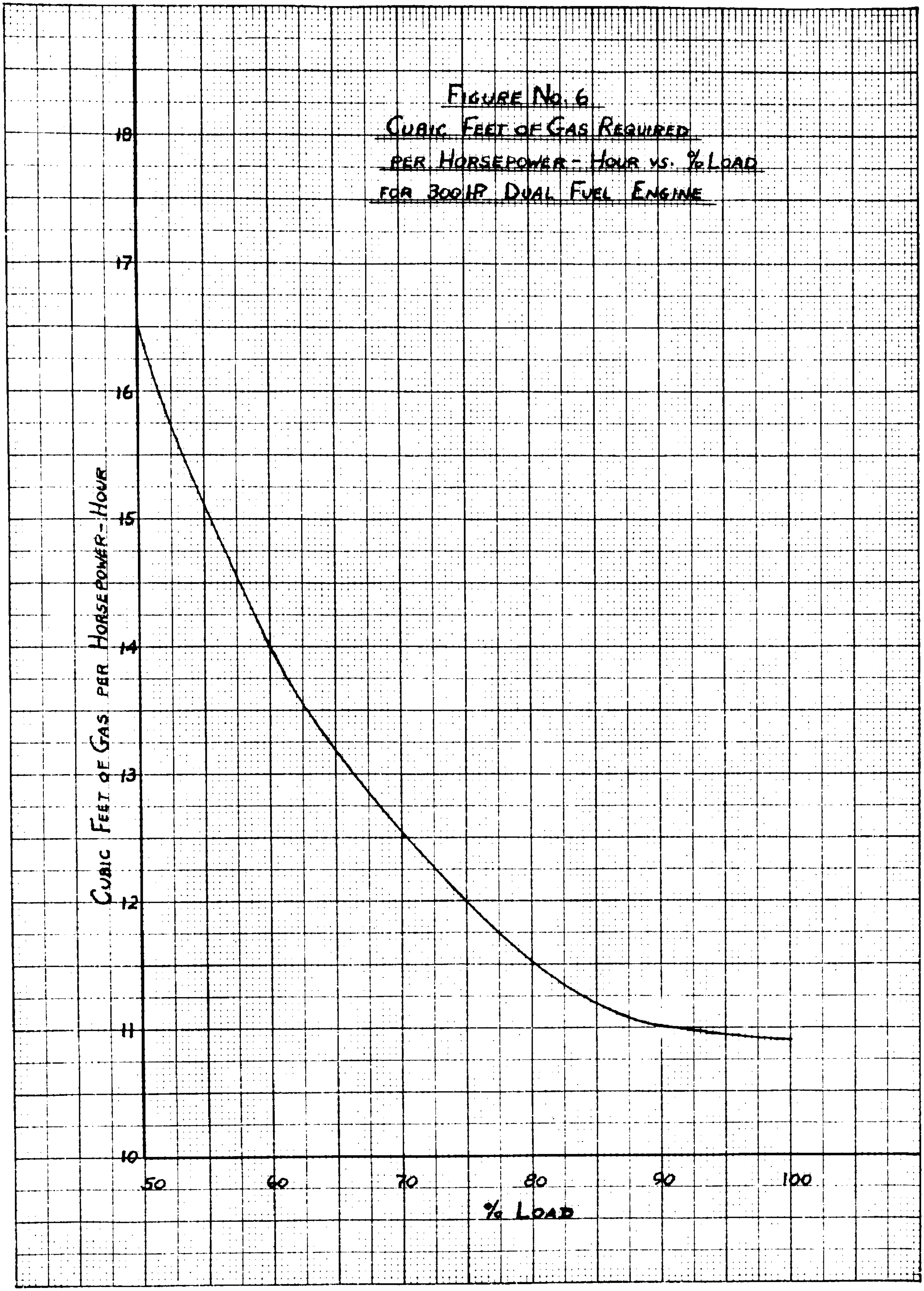


Figure No. 6
Cubic Feet of Gas Required
per Horsepower - Hour vs. % Load
for 300 HP Dual Fuel Engine
Cubic Feet of Gas per Horsepower - Hour
18
17
16
15
14
13
12
11
10
50
60
70
80
90
100
% Load

Data for several New York City Plants, show the following:

Table No. 3

Daily Gas Output and Population Data for Plants in Operation

	Tallmans Island	Jamaica	Bowery Bay
Daily gas output over a monthly period--cu. ft.			
Maximum	199,000	385,700	298,700
Average	186,600	352,040	248,920
Minimum	175,000	309,000	147,900
Population Data by above methods			
1.............	126,000	263,000	291,000
2.............	118,000	263,000	291,000
3.............	115,000	232,000	308,000

From the above data, the following figures result for maximum, average, and minimum gas production:

Table No. 4

Gas Production for Plants in Operation

Plant	Population Basis	Daily Gas Production Over a Monthly period-cu.ft.per capita: Maximum	Average	Minimum
Tallmans Island	1	1.58	1.48	1.39
	2	1.69	1.58	1.48
	3	1.73	1.62	1.52
Jamaica	1	1.47	1.34	1.18
	2	1.47	1.34	1.18
	3	1.66	1.52	1.33
Bowery Bay	1	1.03	0.86	0.51
	2	1.03	0.86	0.51
	3	0.97	0.81	0.48

Except for Bowery Bay where gas production has been more variable than at the other plants, it seems as if a considerably higher gas production than one cubic foot per capita is likely on the above basis. However, the figure of one cubic foot per capita will be adopted as a conservative estimate for gas production to be expected from the plant.

Table No. 5

Sewage Gas Available and Amount Required

	Present		Future	
	Winter	Summer	Winter	Summer
Population	40,000	90,000	88,000	180,000
Gas Produced				
1.0 cu.ft./capita basis (cu.ft./hr.)	1,667	3,750	3,670	7,500
1.1 cu.ft./capita basis (cu.ft./hr.)	1,830	4,120	4,040	8,250
Recapitulation of Gas Demand				
Minimum flow (cu.ft./hr.)	2,990	5,000	5,710	8,450
Average flow (cu.ft./hr.)	3,050	5,240	6,110	9,150
Maximum flow (cu.ft./hr.)	4,940	5,950	7,940	12,140

Therefore, the plant cannot be operated entirely on sewage gas, but the gas produced will have to be supplemented. Gas storage facilities, as shown by the above analysis, need not be provided.

III. Engines and Auxiliaries for a Sewage Treatment Plant

A. Comparison of Performance Characteristics of Available Engines.

Until about five years ago, the only engines available for sewage treatment plant uses were low compression, spark-ignition, four cycle gas engines. These engines have substantially the following characteristics:

1. Ignition of the mixture of sewage gas and combustion air at 120 to 125 p.s.i.

2. Mean effective pressure, 65 to 70 p.s.i.

3. Piston speed usually under 1200 feet per minute.

4. Consumption of sludge gas, based on a calorific value of 650 B.T.U. per cubic foot, is about 15 to 15.5 cubic feet per B.H.P. -hour. When operating on utility gas, with 535 B.T.U. per cubic foot, consumption is about 18.5 to 19 cubic feet per B.H.P.-hour.

5. Thermal efficiency is about 25 per cent. However, the combined, overall efficiency of both engines and waste heat recovery, so very important for sludge and space heating, is approximately 80 per cent due to the high exhaust temperatures and the high heat content in engine circulating water and exhaust.

In recent years, the dual fuel engine has become available. This type of engine can operate either entirely on gas, entirely on fuel oil, or on any combination of gas and oil. The change from gas to oil can be made either by hand or by automatic control while the engine is running under load. The dual fuel engine operates at diesel pressures with diesel efficiencies. These engines offer great advantages to sewage treatment plants where gas production is neither fairly constant nor often, particularly in activated sludge plants. Here, gas production is insufficient, while the load on the engines fluctuates considerably. These engines, operating entirely on fuel oil during the starting-up period of a plant, eliminate the need of providing for purchased gas until plant gas production is adequate.

The first dual fuel type of engine suitable for sewage treatment plant use was developed in 1940 by the National Gas and Oil Engine Co. of

England. In 1941 to 1943, the leading American diesel builders began design and development of an engine similar to the British type, featuring high compression of the gas and air mixture, and capable of switching fuels while operating. In 1944, the first dual fuel engine was put into operation at the Tallmans Island Sewage Treatment Works in New York City.

The dual fuel engine has been officially defined by the Diesel Engine Manufacturers Association as "one which uses all fuel on the diesel cycle, or predominantly gaseous fuel with oil fuel ignition, and is fully convertible from one fuel to the other." A gas-diesel engine is therefore a dual fuel engine that is not instantly convertible.

While the compression of the gas-air mixture in the dual fuel engine is considerably higher than in a low compression gas engine, being usually about 425 to 450 p.s.i., the mean effective pressure of 75 to 80 p.s.i. is not very much higher.

It was found that under such conditions of high compression, ignition by spark could not be used. It therefore became necessary to ignite the mixture by the injection of a small amount of pilot fuel oil during the compression stroke in order to initiate, propagate, and sustain ignition. The dual fuel engine apparently violates all the rules by mixing fuel and air before compression and then raising the mixture to high pressures. Preignition does not occur, but burning is started and maintained by the pilot oil injection into the heated mixture. The mount of pilot oil thus required is about 5 to 7% of the total B.T.U. requirement, at rated full engine output, and remains constant over the whole load range. It is injected usually by a small, high pressure, multi-cylinder pump, which is driven by the engine.

The gas consumption in dual fuel engines is considerably lower than in the low compression, spark ignition, gas engine. With sewage gas of 650 B.T.U. per cubic foot and 5% of total B.T.U. input for pilot oil, the gas required is only about 11.0 cubic feet per B.H.P.-hr., or about 27-30% less than in low compression gas engines.

The difference in fuel-air ratios between these engines and conventional gas and gasoline engines probably accounts for differences in ignition. Gas engines operate with a nearly perfect mixture, readily ignited and explosive on its burning. The dual fuel engine, being essentially a diesel, operates with high excess air, or a "lean" mixture. Even at high temperatures, such a mixture does not self-ignite in the short time available.

The power output from an engine of the same number of cylinders, bore, stroke and R.P.M., can be increased about 50% by supercharging a dual fuel engine. Combustion air, in this case, is supplied to the engine under pressure by a turbocharger mounted on the engine using exhaust gas to drive a turbine. Higher pressure of air, and therefore larger volume of free air supplied, permits burning more fuel than is possible with non-supercharged engines in the same size cylinder. Compression of the air-gas mixture in supercharged engines is about the same as in non-supercharged, but the mean effective pressure is considerably higher, being usually about 112 to 120 p.s.i. The thermal efficiency of dual fuel engines, either supercharged or non-supercharged, is substantially the same as for diesel engines, i.e., about 34 to 35%.

Supercharged engines usually show somewhat better fuel economy than non-supercharged units. Increase in output depends on a variety of factors. Capacity boosts from 30 to 80% have been reported and 40% may be taken as a conservative value. Superchargers may be added to existing engines and the capacity gained in this way may be substantially less expensive than an installation of additional engines.

The energy in hot exhaust gases from a diesel can be recovered in a gas turbine to drive a centrifugal blower supplying air at supercharging pressure. Usually turbine and blower rotors are mounted on a common shaft in a single casing. Such a unit is called a turbocharger.

In the Buchi turbocharging system, valve timing, exhaust manifolding and turbine design are coordinated to create timed pressure pulsations. Engines of four cylinders and over employ a multiple exhaust manifold arrangement, to permit complete scavenging of one cylinder before the exhaust valve opens on another. No controls are needed. Speed, air quantity and charging pressure follow engine load and speed changes.

A comparison of the operating characteristics of a spark-ignition gas, dual fuel, and conventional diesel engines is given below.

a. Spark-Ignition Gas Engine

1. Fuel introduced by mixing valve which blends the air and gas fuel in proper proportions outside the cylinder before compression.

2. Suction stroke, with intake valve open, fills the cylinder with mixture.

3. Compression stroke raises mixture pressure to 75 to 300 p.s.i.

4. Spark ignites mixture near end of compression stroke.

5. Fired mixture expands, forcing the piston downward on its power stroke.

6. Exhaust valve opens and rising piston clears the cylinder of burned gas.

b. Dual Fuel Engine

1. Fuel enters intake-air stream near inlet valve and mixes before compression outside the cylinder.

2. Inlet valve opens and suction stroke fills the cylinder with air and fuel.

3. Compression stroke raises pressure of mixture to about 450 p.s.i.

4. Near the end of compression, pilot oil is injected to initiate combustion.

5. Heat of compression ignites pilot oil, which causes mixture to burn and the resulting expansion pushes the piston downward.

6. Exhaust valve opens and the rising piston clears the cylinder.

c. Conventional Diesel Engine

1. Suction stroke, with inlet valve open, fills cylinder with air.

2. Compression stroke raises pressure to about 450 p.s.i.

3. High-pressure fuel injection starts at or near the end of the compression stroke inside the cylinder.

4. High air temperture, caused by compression, ignites fuel.

5. Burning mixture expands, pushing piston downward on its power stroke.

6. Exhaust valve opens and the rising piston clears the cylinder.

Many dual fuel engines are operating in practically every type of stationary service in sizes ranging from 125 H.P. to 3500 H.P. Dual fuel engines have been perfected to the point where, by comparison with the conventional high-grade spark engine, they require 30 per cent less fuel at full load and 50 per cent less fuel at quarter load. By supercharging, the output of any given size engine has been increased as much as 75%. This increased power from a given foundation and engine size appreciably reduces the building and installation costs.

Comparative fuel consumptions for various four-cycle engines on a net heat value basis is shown in Figure No. 7, page 30.

Gas engines have been in successful operation in sewage treatment plants since the 1930's. Performance curves for a 4-cycle spark ignition gas engine are shown in Figure 8, page 31.

They have made a good record, but from a knowledge of disposal plant operations it is believed that the dual fuel engine is even better fitted for this service because;

1. It provides a source of power as a diesel engine to put the sewage disposal plant into operation, thus freeing the plant from standby charges for electrical power.

2. It lessens the need for separate heating equipment both for the building and for starting the digestion process, as the waste heat boilers and jacket water provide the necessary heat. This combination provides an overall thermal efficiency of 65 per cent.

3. It is a source of a definite amount of dependable power at all times. If the sewage gas supply is not enough to meet the power demand, fuel oil will automatically make up the additional fuel requirements.

4. It will give long life due to extremely thorough combustion and relatively low operating temperatures.

Recent developments, such as running the gas through purifiers,

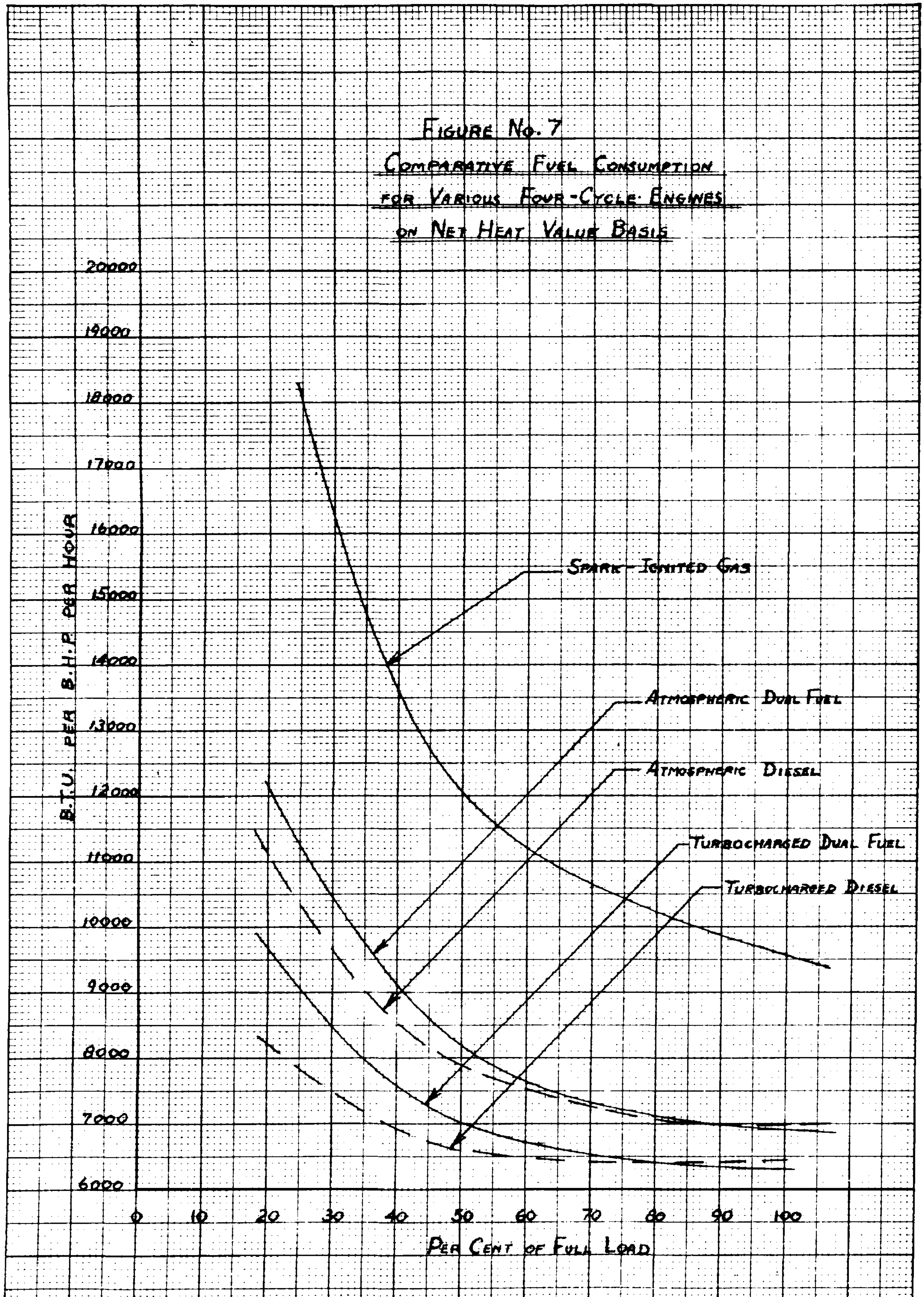


FIGURE No. 7
COMPARATIVE FUEL CONSUMPTION
FOR VARIOUS FOUR-CYCLE ENGINES
ON NET HEAT VALUE BASIS
B.T.U. PER B.H.P. PER HOUR
20000
19000
18000
17000
16000
15000
14000
13000
12000
11000
10000
9000
8000
7000
6000
0
10
20
30
40
50
60
70
80
90
100
PER CENT OF FULL LOAD
SPARK-IGNITED GAS
ATMOSPHERIC DUAL FUEL
ATMOSPHERIC DIESEL
TURBOCHARGED DUAL FUEL
TURBOCHARGED DIESEL

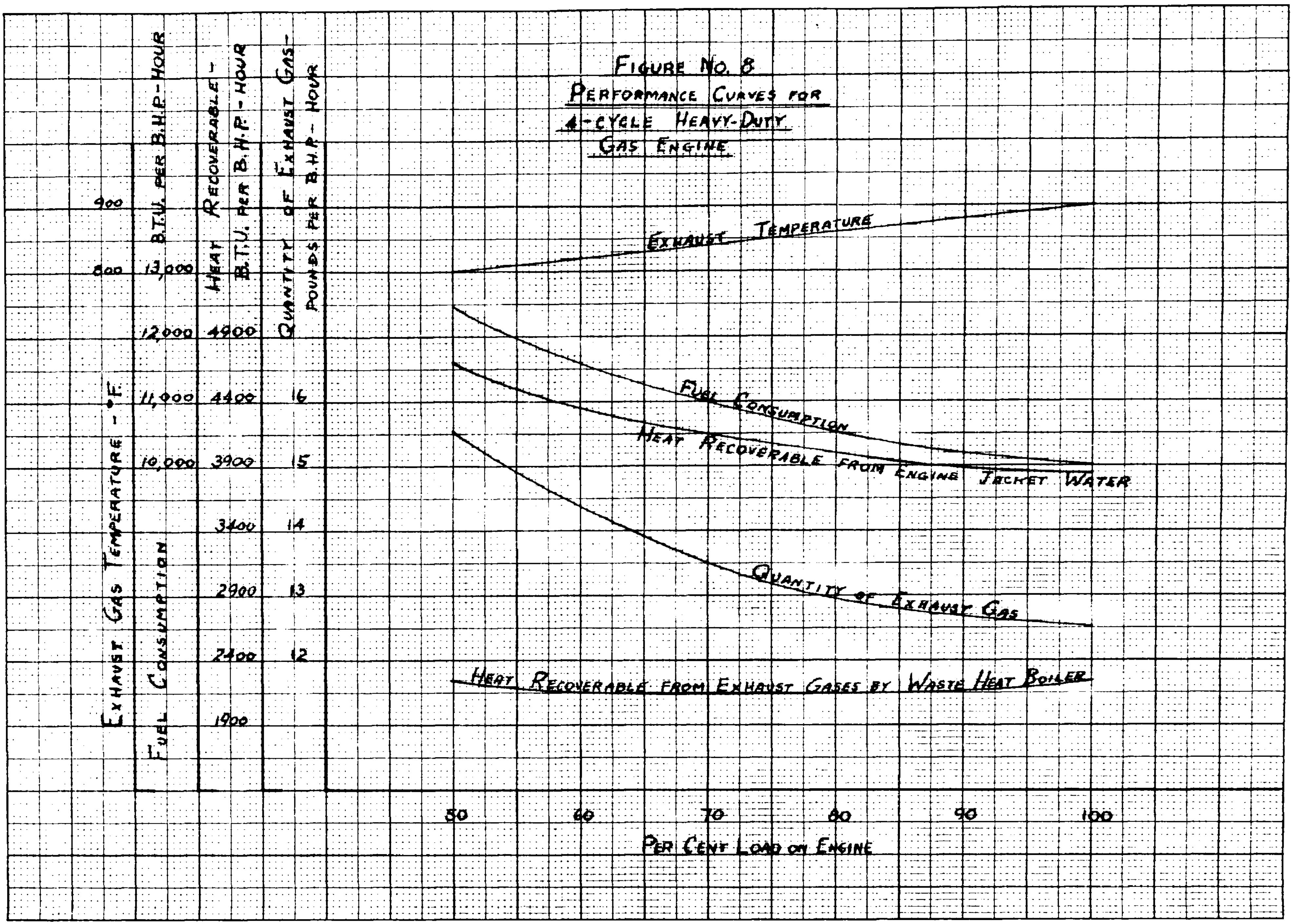


FIGURE NO. 8
PERFORMANCE CURVES FOR
4-CYCLE HEAVY-DUTY
GAS ENGINE
EXHAUST GAS TEMPERATURE - °F
FUEL CONSUMPTION B.T.U. PER B.H.P.-HOUR
HEAT RECOVERABLE - B.T.U. PER B.H.P.-HOUR
QUANTITY OF EXHAUST GAS - POUNDS PER B.H.P.-HOUR
900
800
13,000
12,000
11,000
10,000
4900
4400
3900
3400
2900
2400
1900
16
15
14
13
12
EXHAUST TEMPERATURE
FUEL CONSUMPTION
HEAT RECOVERABLE FROM ENGINE JACKET WATER
QUANTITY OF EXHAUST GAS
HEAT RECOVERABLE FROM EXHAUST GASES BY WASTE HEAT BOILER
50
60
70
80
90
100
PER CENT LOAD ON ENGINE

effective protection of the parts against the corrosive action of sewage gas, use of chrome-plated top ring, and basic-type lubricating oils, promise to reduce cylinder and valve wear to that obtainable with the use of the highest grade of fuels.

With the higher cost of fuel and the greater amount of power obtainable from each cubic foot of sewage gas, it is definitely indicated that more and more dual fuel engines will be used in sewage treatment plants;

Table No. 6

Representative Dissipation of Energy in Diesel and Gas Engines.

	Diesel Engine	Gas Engine (spark ignition)
1. Useful work-actual net power of the engine. This figure, divided by the total energy of the fuel, equals thermal efficiency................	34%	25%
2. Jacket loss-heat absorbed from combustion zone by water in surrounding cooling jackets	30%	30%
3. Exhaust and radiation loss-heat carried away in hot exhaust gas and heat radiated from engine and exhaust piping.............	27%	38%
4. Friction loss-friction of crankshaft, connecting rod and other bearings, and pistons. This loss is also dissipated as heat.......	9%	7%
	100%	100%

Fuel Consumption- Guarantees of fuel consumption are expressed in pounds of fuel per net brake-horsepower hour at one-half, three-quarters and full load when operating at rated speed. Fuel oil and pilot oil consumptions are based on the higher heating value of 19,350 B.T.U. per pound. Fuel consumption of gas-burning and dual fuel diesels is guaranteed in terms of B.T.U. per net brake-horsepower-hour, based on the low heat value because gaseous fuels vary widely in heating value.

The principal gaseous products of the biolysis of organic matter are methane and carbon dioxide. The B.T.U. content of the gas is a function of the percentage of methane, the temperature, the pressure, and the water vapor in the gas. Gas saturated with water vapor at 60 degrees Fahrenheit, and 30 inches of mercury pressure has, for example, a net heat value in B.T.U. per cubic foot of approximately nine times the percentage of methane expressed as a whole number. For dry gas the factor is 9.2. The entire net value is available under a boiler or in an internal-combustion engine.

A heat balance for a dual fuel engine rated as follows is given in table No. 7:

9" x 10½" - 8 cylinder-rated 306.5 B.H.P. @ 600 R.P.M. - 75 lbs. B.M.E.P.

Table No. 7

Heat Balance — Diesel Operation (High heat value)

	Load: Full	3/4	1/2
Total input to engine, B.T.U./hr......	2,400,000	1,892,000	1,364,000
Rejected to jacket water B.T.U./hr......	797,000	598,000	398,000
Rejected to lube oil, B.T.U./hr......	138,000	103,500	68,800
Useful work, ... B.T.U./hr......	778,000	584,000	389,000
Rejected to exhaust gases B.T.U./hr......	577,000	530,000	438,000
Friction, radiation and unaccounted-for-losses, B.T.U./hr......	110,000	76,500	56,200
Typical exhaust temperature, degree F.......	725°	600°	460°

Normal Jacket water temp. °F. Inlet ... 140° Outlet 160°
Normal Lube oil temp., °F. Inlet ... 135° Outlet 150°

Heat Balance — Dual Fuel Operation (low heat value)

	Load: Full	3/4	1/2
Total input to engine, B.T.U./hr.........	2,180,000	1,817,000	1,460,000
Rejected to jacket water B.T.U./hr.........	674,000	575,000	489,000
Rejected to lube oil, B.T.U./hr.........	138,000	103,500	68,800
Useful work, B.T.U./hr.........	778,000	584,000	389,000
Rejected to exhaust gases B.T.U./hr.........	502,000	480,000	453,000
Friction, radiation, and unaccounted-for-losses, B.T.U./hr.........	88,000	74,500	60,200
Typical exhaust temperature, degree F..........	800°	670°	555°

Normal jacket water temp. °F. Inlet.... 140° Outlet 160°
Normal lube oil temp.... °F. Inlet.... 135° Outlet 150°

At full load, fuel consumption = $\frac{2,180,000}{306.5}$ = 7100 B.T.U./B.H.P./hr.

If pilot oil = 7% 500 B.T.U./HP-hr., then

$$\frac{\text{lbs. of pilot oil}}{\text{HP-hr.}} = \frac{500}{19,350} = 0.026$$

Dual Fuel Operation

	Full Load	3/4	1/2
B.T.U./HP/hr. total	7,100	7,900	9,540
B.T.U./HP/hr. in gas	6,600	7,400	9,040
Cubic feet gas/HP/hr.	11.0	12.35	15.0

B. Waste Heat Recovery

The heat absorbed by engine cooling water and contained in exhaust gases is approximately 60 to 65% of the total heat content in the fuel, depending on the type of engine.

All the heat contained in the cooling water, except small amounts lost in radiation, and about 50 to 60% of heat in the exhaust gas, can be recovered in heat exchangers and used for sludge and space heating.

The amount of recoverable heat depends upon the type of engine used. With low-compression gas engines using about 10,000 B.T.U. in fuel per B.H.P.-hr. about 6,000 B.T.U. per B.H.P.-hr., or 60% can be recovered. With dual fuel engines, using about 7,500 B.T.U. in fuel per B.H.P.-hr., the amount of heat recoverable is about 4,125 B.T.U. per B.H.P.-hr., or 55% of the total heat input.

This recovered heat can be used either in the form of hot water solely, or hot water combined with steam, as may be required. With purchased electric power for driving plant machinery, purchased oil or gas would have to be used to provide for sludge and space heating involving additional costs.

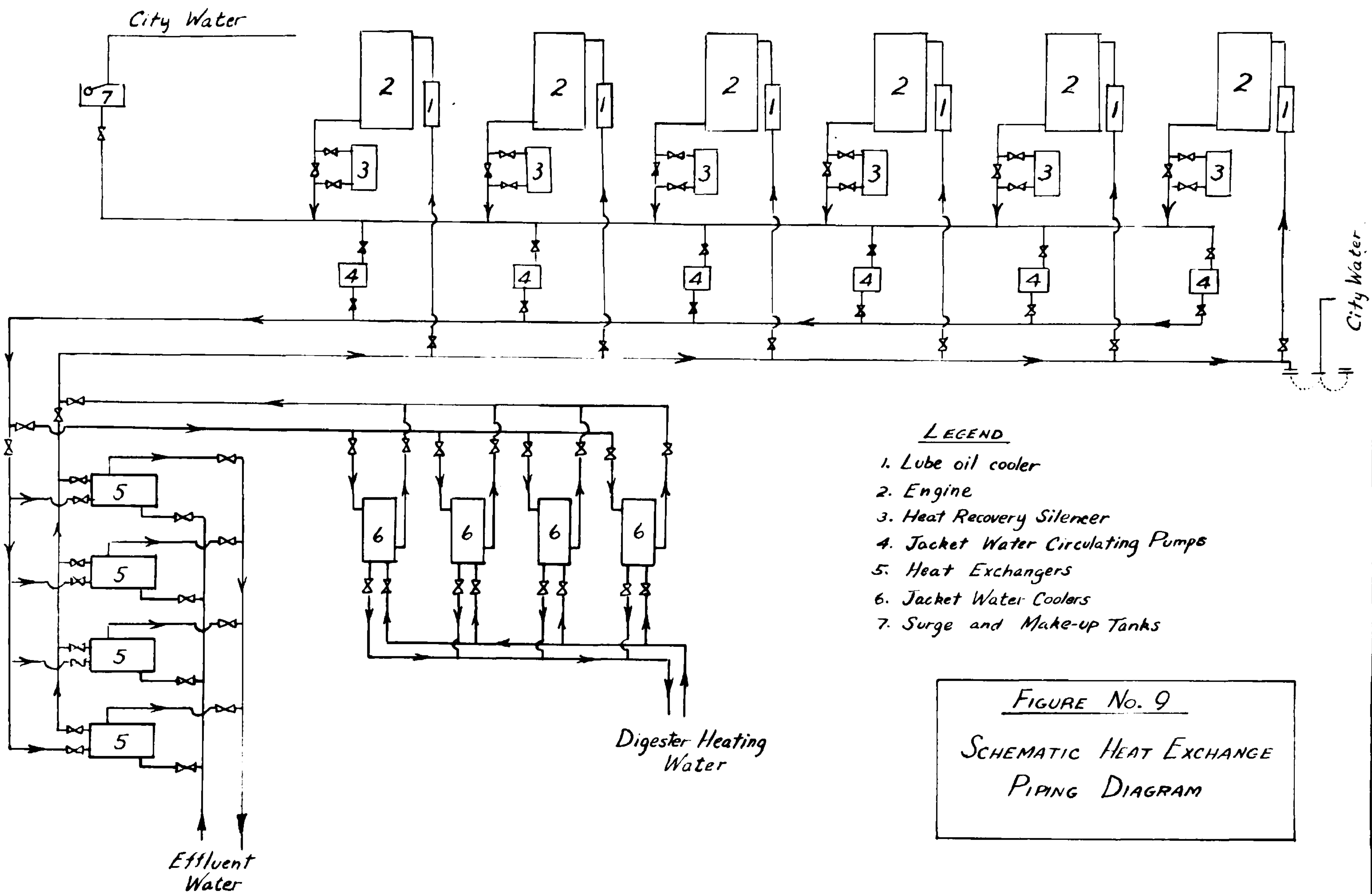
C. Engine Cooling

The engine cooling water is supplied by motor-driven centrifugal pumps, of which there is one for each engine. The capacity of the pumps is governed by the desired temperature rise of water circulating through the engine. Usually this temperature rise is about 25° F. with temperature at the inlet to the engine of about 115° to 125° F.

The engine cooling water cycle is as follows:
After leaving the cylinder jackets of the engines, at about 140° to 150°, the water is passed through exhaust gas heaters, or through heat recovery exhaust silencers, where it absorbs all the available heat in the exhaust gas. Finally, after passing further through water to water heat exchangers or through sludge heaters, where the absorbed heat is given up, the water is returned to the engine. In utilizing this waste heat, the system must be designed to avoid any possible contamination of engine cooling water by sludge.

If the heat produced by the engines is not all needed for sludge and space heating, as for instance in the summer time, the water on its way back to the engines is passed through coolers where it is cooled to the desired engine jacket inlet temperature. A schematic heat exchange piping diagram is given in Figure No. 9.

In recent years, a new system of engine cooling, known as the "Vapor Phase" system, has been developed. Figure No. 10 shows a typical schematic cooling and make-up water diagram. Before starting the engines, the system is filled with water and when the water jackets, exhaust gas



LEGEND

1. Lube oil cooler
2. Engine
3. Heat Recovery Silencer
4. Jacket Water Circulating Pumps
5. Heat Exchangers
6. Jacket Water Coolers
7. Surge and Make-up Tanks

FIGURE No. 9

SCHEMATIC HEAT EXCHANGE PIPING DIAGRAM

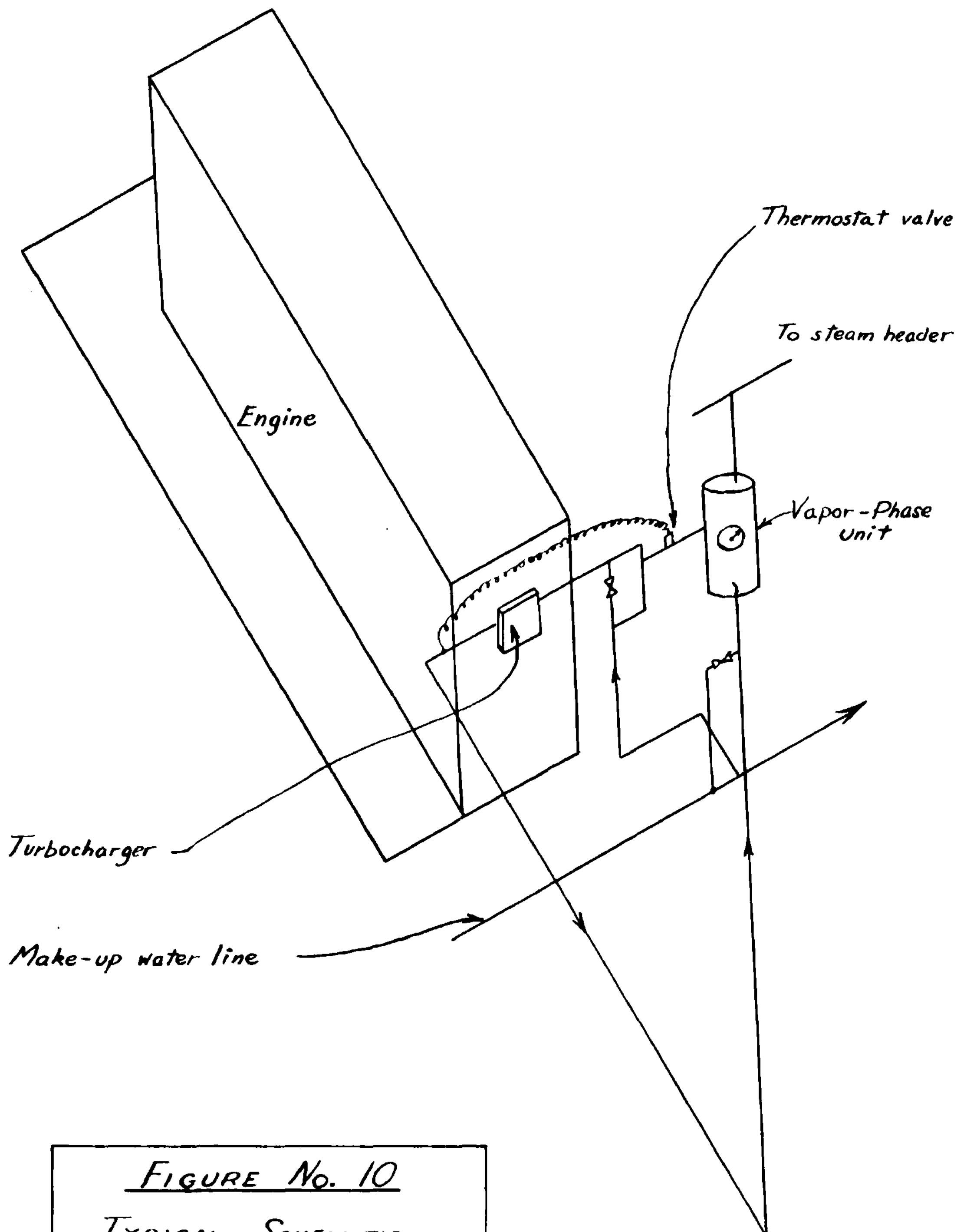


FIGURE NO. 10

TYPICAL SCHEMATIC

COOLING AND MAKE-UP

WATER DIAGRAM

boiler, and steam separating unit of the vapor phase system are full, the engine may be started.

Upon starting, the engine water pump, taking suction from the steam separating unit, circulates the water through the water jackets, where it absorbs the heat of combustion that is rejected to the water. It then passes through the exhaust gas boiler, where the exhaust waste heat is picked up by the same water, finally flowing to the steam separating unit, and forming steam of about 5 to 10 p.s.i.

As no cooling of the water other than radiation occurs in this cycle, the water temperature rises to its elevated boiling point and begins to produce steam. At this time the steam is separated from the water and passes to the main steam header to be used for sludge and space heating. Return condensate together with additional treated make-up water is returned to the jackets by the engine pump.

The treated make-up water is supplied from the plant source to the engine turbocharger for cooling this unit. The water is thermostatically controlled so as to maintain the turbocharger jacket water at the required temperature. After cooling the turbocharger, the water passes to the steam separating unit as make-up water.

The amount of water required to cool the turbocharger is greater than that required to replace the engine water evaporated into steam supplied to the digesters. This excess of water builds up in the steam separating unit to a predetermined height when a high level float valve causes the blow-down valve to open, passing the excess water to the sewer. When the blow-down reaches a predetermined level in the steam separating unit, the low level float valve causes the blow-down valve to close.

The blow-down cycle is controlled by the amount of load imposed upon the engine. When the engine is fully loaded, the blow-down will occur more frequently than when lightly loaded.

In the event that steam requirements are reduced, provisions are made for by-passing the water around the waste heat boilers directly to the steam separators.

The steam separators are equipped with a low water alarm actuating device to notify the operator when the water is low in the steam separating unit. Thus the water level can be raised or the engine shut down before the water reaches a point low enough to affect circulation. The separators are also equipped with safety release valves, set to open at slightly above the maximum operating pressure of the system. Should the steam process be cut down or shut off, these safety valves will open and pass the steam to the atmosphere, allowing the engine to continue operation for as long and at as high a load as may be required.

In addition to providing steam, the vapor phase system has additional advantages with respect to engine operation. Engine sludging is reduced since operation is above the dew point of the combustion gases. Elimination of condensation reduces sludging with all the resultant benefits. It also stops the formation of sulfuric acid which is the product of condensate in conjunction with hydrogen sulfide normally found in sewage gas and other fuels. Cleaner combustion with all its attending advantages including fuller utilization of fuel are attributed to this system as well as the ability to burn raw or "sour" gas with no bad effects. Other advantages claimed for this system are:

1. Fastens heat transfer from engine cylinders to the jacket cooling water.

2. More uniform liner-wall temperature resulting in uniform piston-cylinder clearance during the full stroke.

3. Prevention of condensation within the cylinders, resulting in less liner and piston wear.

4. Increased mechanical efficiency.

5. Reduced cost of engine maintenance.

D. Starting and Combustion Air

The starting system provides motive power to turn the engine through several cycles until firing starts and the unit runs on its own power.

The air for starting the engine is supplied by motor-driven displacement type compressors, usually two in number, and is stored in air tanks. The capacity of compressors and the number and size of air tanks depend on the size and number of engines in the power plant. The pressure of air is usually kept at 250 p.s.i., although most of the engines will start at 160 p.s.i. and less, thus permitting several consecutive starts of an engine.

A small gasoline engine driven, or battery operated compressor is generally installed for stand-by against loss of power supply.

All the air used for combustion must be thoroughly filtered. Any dust or grit that passed in with the air accumulates in the valve passages, on the valves and cylinder wall surfaces, causing excessive cylinder wear. However, the service does not require the costly automatic filters used for aeration tank diffusers.

Where small engines are used, the filters may be mounted on the engine themselves, drawing air directly from the engine room, but with a number of large engines, requiring considerably greater quantities of combustion air, the latter must be drawn from the outside of the building. This avoids excessive lowering of engine room temperature in the winter time.

There are two principal types of air filters, the dry and wet respectively.

The dry type depends upon fabric stretched over several layers of wire screens. The wet type works on the adhesive impingement principle. This filter consists of galvanized metal strands crimped and packed into frames and wetted with a viscous fluid that removes and holds the dust particles. The frames should be capable of easy removal for cleaning. The efficiency of filters gradually diminishes with use, until the dry filters are cleaned or until the wetting fluid is renewed in the wet filters.

In all cases the filter elements must be of sufficiently large area to minimize the pressure loss as the air passes through. To avoid too frequent cleaning, it is advisable to have their operating capacity about 60 to 70% of manufacturer's rated capacity.

E. Lubrication

Lubrication of a diesel engine breaks down into three parts:

1. Providing an oil film between shafts and bearing surfaces at main, crankpin and wristpin bearings.

2. Performing the same job for camshaft, valve gear and various engine auxiliaries, and

3. Maintaining an oil film between piston and cylinder walls.

The oil for bearing lubrication and for piston cooling is drawn from the sump of the engine by a rotary pump driven by the engine and is forced through the strainer, oil cooler, bearings and pistons and is finally returned to the sump, thus insuring continuous flow.

For cylinder lubrication, separate mechanical lubricators usually consisting of a group of small reciprocating pumps mounted in a single casing, which serves as an oil reservoir are used. The pumps supply a measured quantity of oil at each stroke and are driven from the engine by an eccentric, crank and ratchet, or gearing. The amount of oil fed by each cylinder is usually separately adjustable. Control is obtained by varying the pump stroke or changing the position of the sleeve parts.

A separate motor driven rotary pump is also usually provided for each engine, to be used during the starting up of the engine, before the latter reaches speed and the engine lubrication system comes to full operation.

One or two storage tanks, of sufficient capacity, with necessary transfer pumps, must also be installed for storage and handling of new make-up oil.

The lubricating oil will not circulate through the engine very long without getting contaminated. This contamination is caused by fuel and water leakage, condensation, dirt or metallic particles, carbonation and sludge, requiring that the oil be cleaned.

The usual cleaning devices offer a choice of centrifugal purifiers, filters using fabric or Fuller's earth as filtering medium, refiners, or a combination of these means.

Purification of lubricating oil can be accomplished by two methods, continuous or batch processes. In the former process the oil, or part of it, circulating through the engines is continuously cleaned and thus is maintained in the best of condition. In the second process, a batch of oil is withdrawn from the system intermittently and put through the cleaning process, after which it is returned to the engines.

The choice of method and equipment for lubricating oil cleaning depends mainly upon the size and type of engine installation. In large power plants, the desired high efficiency of purification will fully justify a complete though relatively expensive installation.

IV. Effect of Heating Requirements on Plant Design

The design of the heating equipment to maintain a desired temperature in the digesters requires a study of the heat balance in the tanks. Heat is required to raise the incoming sludge to the optimum temperature and to compensate for losses to the surrounding air.

The heat required to raise the incoming sludge to digester temperature is shown in table No. 8.

Table No. 8

Sludge Heating Requirements (Excluding Radiation)

		1950	1970
Population			
Winter Population		40,000	88,000
Summer Population		90,000	180,000
Sludge to Digesters			
Per Capita-lbs./day		0.25	0.25
Total—Dry lbs./day	Winter	8,740	17,250
	Summer	19,100	39,100
Liquid—lbs./day @5% solids....	Winter	174,800	345,000
	Summer	382,000	782,000
Average temperature °F:			
	Winter	50	50
	Summer	65	65
Temperature of Sludge in Digesters - °F.......		85	85
Heat Required for Incoming Sludge			
Million B.T.U./day	Winter	6.1	12.1
	Summer	7.6	15.6
Million B. T. U./hr.	Winter	0.254	0.505
	Summer	0.316	0.650

Digester Heat Losses

Average overall value of heat-transfer coefficient equals 0.10 B.T.U./hr./ft.^{2} tank surface /°F. (Haseltine). This assumes that roof insulation is almost equivalent to an earth cover.

Design capacity for tanks equals 2 cubic ft./ capita for summer population, or 180,000 cu. ft. total volume. Gas production was previously shown to be 1.0 to 1.1 cubic ft./ capita. Using four-50 ft. diameter tanks, the volume of each tank is 45,000 cubic feet.

$$\text{Depth of each tank required} = \frac{45{,}000}{\frac{\pi \times 2{,}500}{4}} = 22.9 \text{ feet}$$

Digesters will have floating covers to maintain a constant pressure on the gas. Take total depth as 30 feet.

The total area of the roof, walls and bottom may now be calculated;

$$\text{Roof and floor area} = \frac{2 \times \pi \times (50)^2}{4} = 3{,}850 \text{ ft}^2.$$

$$\text{Wall area} = \pi \times 50 \times 30 = \underline{4{,}710}$$

$$\text{area} = 8{,}560 \text{ ft}^2. \text{ per tank}$$

$$\text{therefore, total digester area} = 4 \times 8560 = 34{,}240 \text{ ft}^2.$$

Table No. 9

Digester Heat Losses (Radiation) - Tank Temperature 85° F.

Outside Temp. °F.	Temp. Difference °F	Heat loss-BTU/hr. Q = KAΔT
20	65	222,000
30	55	188,000
40	45	154,000
50	35	119,800
60	25	85,500
70	15	51,300
80	5	17,100

Figure No. 11 illustrates digester heat loss by radiation as a function of the outside temperature. The total heat required to heat the sludge, including radiation, is shown in Table No. 10.

Table No. 10

Sludge Heating (Including Radiation Loss)

Heat Required-Million BTU/hr.

Month	Average Air Temp.	Raw Sludge Temp.	Raw Sludge 1950	Raw Sludge 1970	Radiation	TOTAL 1950	TOTAL 1970
January	31	50	0.254	0.505	0.18	0.43	0.69
February	31	50	0.254	0.505	0.18	0.43	0.69
March	38	50	0.254	0.505	0.16	0.41	0.67
April	49	50	0.254	0.505	0.12	0.37	0.63
May	61	55	0.254	0.505	0.09	0.34	0.60
June	69	65	0.316	0.650	0.05	0.37	0.70
July	74	65	0.316	0.650	0.03	0.35	0.68
August	75	65	0.316	0.650	0.03	0.35	0.68
September	67	65	0.316	0.650	0.05	0.37	0.70
October	56	50	0.254	0.505	0.10	0.35	0.61
November	44	50	0.254	0.505	0.14	0.39	0.65
December	35	50	0.254	0.505	0.17	0.42	0.68
					Total..........	4.58	7.98
					Average.......	0.382	0.665

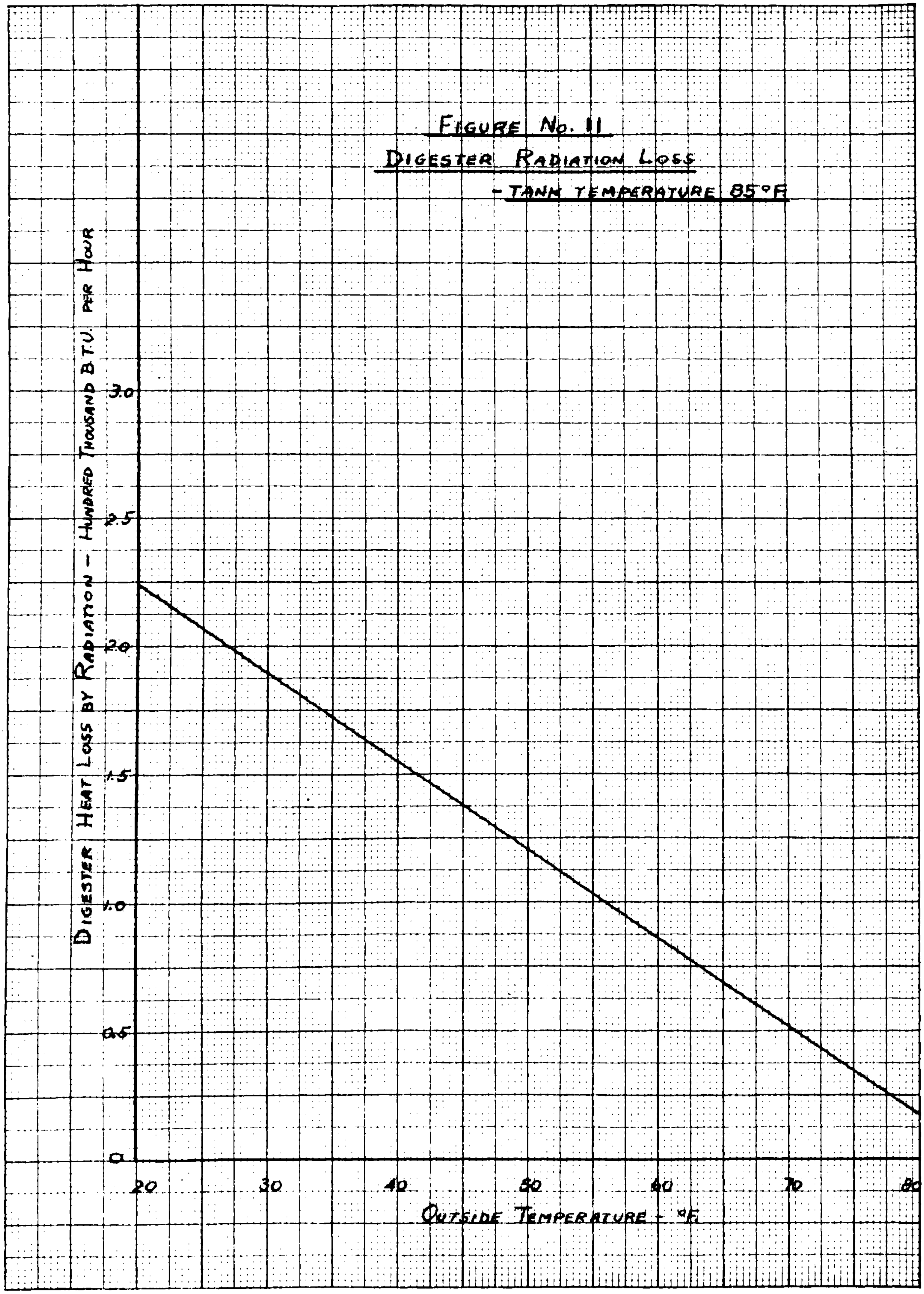


Figure No. 11
Digester Radiation Loss
- Tank temperature 85°F
Digester Heat Loss by Radiation - Hundred Thousand B.T.U. per Hour
3.0
2.5
2.0
1.5
1.0
0.5
0
20
30
40
50
60
70
80
Outside Temperature - °F.

Consideration can now be given to the space heating requirements. These are distributed among the pump and power house, sludge storage building, grit chambers, sedimentation tank gallery, and the venturi and gas meter building. The cubage, or total volume, of these buildings and temperatures desired to be maintained there must be known before the space heating requirements can be calculated. Since these quantities are obtainable only after the entire plant is designed, the space heating load will be obtained from a plant of similar size with like climatic conditions. The Rockaway Sewage Treatment Works, which was chosen for comparison, has 950 square feet E.D.R. radiators, and 2,800,000 BTU/hr heat transmission from unit heaters.

1 boiler horsepower is equal to 33,472 BTU/hr., and equivalent to approximately 130 square feet E.D.R.

$$\frac{950}{130} \times 33,472 = 275,000 \text{ BTU/hr.}$$

Therefore, the total space heating requirements are approximately 3,075,000 BTU/hr. A design figure of 3,000,000 BTU/hr. at 0°F. outside temperature for the plant to be designed will be used, and the average inside temperature will be taken as 60° F.

Fuel requirements for both space and sludge heating are given in table No. 11.

Table No. 11

Fuel Requirements for Space and Sludge Heating

Month	Av. Outside Temp. °F.	Mil. B.T.U./hr.	*Oil Req'd Gals/day (Space)	#Sludge Gas Required (10^3 cu.ft/day) (Space)	Mil BTU/hr 1950 (Sludge)	Mil BTU/hr 1970 (Sludge)	*Oil Req'd Gals./day 1950 (Sludge)	*Oil Req'd Gals./day 1970 (Sludge)	#Gas Re'd 10^3 cu. ft./day 1950 (Sludge)	#Gas Re'd 10^3 cu. ft./day 1970 (Sludge)
Jan.	31	1.45	331	72	0.43	0.69	98	158	21	34
Feb.	31	1.45	331	72	0.43	0.69	98	158	21	34
March	38	0.73	167	36	0.41	0.67	93	153	20	33
April	49	0.37	85	18	0.37	0.63	84	144	18	31
May	61	- —	—	—	0.34	0.60	78	137	17	30
June	69	- —	—	—	0.37	0.70	84	160	18	35
July	74	- —	—	—	0.35	0.68	80	155	17	34
August	73	- —	—	—	0.35	0.68	80	155	17	34
Sept.	67	- —	—	—	0.37	0.70	84	160	18	35
Oct.	56	0.20	46	10	0.35	0.61	80	139	17	30
Nov.	44	0.80	183	40	0.39	0.65	89	149	19	32
Dec.	35	1.25	285	62	0.42	0.68	96	155	21	34

*1 Gallon of oil produces approximately 105,000 BTU. at point of use.

$$\left(18{,}000 \frac{\text{BTU}}{\text{lb. oil}} \times 7.8 \frac{\text{lbs. oil}}{\text{gal.}} \times 0.75 \text{ eff. of boiler} = 105{,}000 \text{ BTU/gal.}\right)$$

$$\text{Gallons per day} = 1{,}000{,}000 \text{ B T U/hr.} \times 24 \text{ hrs./day} \times \frac{\text{gal.}}{105{,}000 \text{ B T U}} = 228.5 \text{ Factor}$$

#With 640 BTU/cu. ft. sludge gas and 75% boiler efficiency,

$$\text{factor equals } \frac{24 \times 1{,}000}{640 \times 0.75} = 50 \text{ for sludge gas required in thousand cu. ft./day}$$

A. **Project I** - All power derived from dual fuel engine-driven generators using available sludge gas supplemented with purchased oil; no utility power. Heat would have to be obtained from an oil fired boiler supplemented by that recovered from engine jacket water and exhaust.

Table No. 12

Dual Fuel Engine Heat

	1950-Winter				1970-Winter			
	Min.	Aver.	Daily Peak	Max.	Min.	Aver.	Daily Peak	Max.
Load-kw.	197	208	228	232	382	416	456	464
* Engine output -HP-	293	310	340	346	570	620	681	720
No. Engines in service.	1	2	2	2	2	3	3	3
#Fuel required-million BTU/hr.	2.17	2.29	2.51	2.56	4.21	4.59	5.04	5.33
Heat value of available gas-mil.BTU/hr.		1.08				2.39		
Heat value of gas,with 6%oil-mil.BTU/hr....		1.14				2.53		
Heat recovery of 55%-mil.BTU/hr.		1.26				2.52		

Table No. 12 (Continued)

	1950 Summer				1970 Summer			
	Min.	Aver.	Daily Peak	Max.	Min.	Aver.	Daily Peak	Max.
Load-kw	281	311	342	404	561	623	685	825
* Engine output -HP....	419	463	510	601	837	929	1020	1210
No. Engines in service.	2	2	2	2	3	4	4	4
# Fuel required million BTU/hr	3.10	3.42	3.77	4.45	6.19	6.87	7.55	8.95
Heat value of available gas-mil.BTU/hr...		2.44				4.60		
Heat value of gas with 6% oil-mil.BTU/hr.		2.59				5.17		
Heat Recovery of 58%-mil.BTU/hr.		1.88				3.77		

* @90% generator efficiency

\# @7400 BTU/HP.-hr.-average heat for 300 HP dual fuel engine-85% load.

Gas production of 1.0 cu. ft. per capita used in above table.

Daily peak taken as 110% of average load.

Rainfall will greatly increase the sewage flows and plant load. Rainfall in the area where the plant is located will be assumed to occur about 8% of the time, and about 80% of the time it is raining, intensities are not sufficient to double the dry weather flow. Furthermore, by control of air quantities the demand during times of rainfall can be controlled to minimize oil purchase. The oil required, in addition to that required at average load, will therefore be estimated as equivalent to running at maximum load 3% of the time. Hence, fuel oil required for the engines will be, using 142,700 BTU/gallon for the oil:

1950-winter- 1.21+(0.03 x 2.56) = 1.29 mil. BTU/hr. = 215 gal/day,

-summer- 0.98+(0.03 x 4.45) = 1.11 mil. BTU/hr. = 186 gal/day,

1970-winter- 2.20+(0.03 x 5.33) = 2.36 mil.BTU/hr. = 397 gal/day.

-summer- 1.99+(0.03 x 8.95) = 2.26 mil. BTU/hr. = 380 gal/day

Table No. 13

Fuel Required for Space and Sludge Heating -- Project I

(oil quantities in thousands of gallons) - 75% boiler efficiency

Month	No. of Days	Oil for Engines 1950	Oil for Engines 1970	Space Heating requirements- (Mil.BTU/hr.)	Space Heating requirements with oil- (Mil.BTU/hr.	Oil Req'd (gals.) X10^3
January	31	6.7	12.3	1.45	0.70	4.95
February	28	6.0	11.1	1.45	0.70	4.48
March	31	6.7	12.3	0.73	- --	- --
April	30	6.5	11.9	0.37	- --	- --
May	31	5.8	11.8	- --	- --	- --
June	30	5.6	11.4	- --	- --	- --
July	31	5.8	11.8	- --	- --	- --
August	31	5.8	11.8	- --	- --	- --
September	30	5.6	11.4	- --	- --	- --
October	31	6.7	12.3	0.20	- --	- --
November	30	6.5	11.9	0.80	0.05	0.34
December	31	6.7	12.3	1.25	0.50	3.54
		74.4	142.3			13.31

It is determined from table No. 12 that an average of 1.26 million BTU per hour will be recovered in the winter of 1950 and 2.58 million BTU per hour in the winter of 1970 from the engine jacket water and exhaust. The average winter sludge heating requirements from table No. 10 are 0.40 million BTU per hour for 1950 and 0.67 million BTU per hour for 1970. There will still remain 186,000 BTU per hour in 1950 and 1,850,000 BTU per hour in 1970. Say, 750,000 BTU per hour in 1950 and 1,600,000 BTU per hour in 1970, will be utilized considering inherent losses. Therefore, the future heating requirements will be satisfied completely by the waste engine heat as shown in table No. 12. For present heating requirements, the plant must provide an additional 700,000 BTU per hour with an oil-fired boiler. Boiler capacity required $= \frac{700,000}{33,472} = 21$ boiler HP. If one boiler horsepower equals 120 square feet EDR, then the boiler will have 2,500 square feet EDR minimum. The quantity of oil required annually for heating, 13,310 gallons, is computed from table No. 13.

B. Project II - partial purchase of power. As in project 1, the heat recovered from the engine jacket water and exhaust will be supplemented by an oil-fired boiler. The sewage pumps will be direct driven by spark-ignition gas engines. These engines require 10,000 BTU per HP. - hour, and the heat recovery is 60%. The high exhaust temperatures and heat content in the engine circulating water and exhaust gas, result in the high heat recovery. Table No. 14 shows heat recovery for this scheme, where the load is due only to the sewage pumps.

Table No. 14

Gas Engine Heat

	1950-Winter				1970-Winter			
	Min.	Aver.	Daily Peak	Max.	Min.	Aver.	Daily Peak	Max.
Load-kw.	52	63	79	87	90	124	155	192
Engine output -HP...	69.7	84.5	106	116.8	121.2	166.2	208	256
No. Engines in service	1	1	1	1	1	2	2	2
* Fuel required-million BTU/hr.		0.845				1.662		
Heat value of available gas-mil.BTU/hr....		1.06				2.39		
Heat recovery @ 60%...... mil.BTU/hr.		0.506				0.998		
	1950-Summer				1970-Summer			
	Min.	Aver.	Daily Peak	Max.	Min.	Aver.	Daily Peak	Max.
Load-kw.	65	93	116	186	124	186	233	388
Engine output -HP.	84.5	124.7	155.5	249	166.2	249	312	520
No. Engines in service.	1	1	2	2	2	2	3	5(future)
* Fuel required-million BTU/hr.		1.247				2.49		
Heat value of available gas-mil.BTU/hr....		2.44				4.88		
Heat recovery @60%-mil.BTU/hr.		0.748				1.492		

* @ 10,000 BTU/HP.-hr. heat rate for spark-ignition gas engine.

Gas production of 1.0 cubic feet per capita used in above table.

Daily sewage flow peak load taken as 125% average.

Therefore 740,000 BTU/hr. will still be available in the winter of 1950, of which 400,000 BTU/hr. are required for sludge heating. Approximately 300,000 BTU/hr. will remain for space heating. An additional 1,150,000 BTU/hr. capacity for present space heating demands must be provided. In the winter of 1970, - 1,700,000 BTU/hr. will be available, 670,000 BTU/hr. of which are to be used for sludge heating. Therefore, 1,030,000 BTU/hr. remain for space heating, which requires an additional 480,000 BTU/hr. to be provided by an oil-fired boiler. Boiler must be designed for present demands. Provide for capacity of 1,150,000/33,472 or 34.5 boiler H.P., and boiler will have 4,140 sq. feet EDR minimum.

The quantity of oil required annually for space heating is shown below in table No. 15.

Table No. 15

Fuel Oil Required for Space Heating — Project 11

Month	No. of days	Space heating Requirements (mil.BTU/hr.)	Space Heating Requirements with oil (mil.BTU/hr.)		Oil Required (10^3 gallons)	
			1950	1970	1950	1970
January	31	1.45	1.15	0.42	8.14	2.97
February	28	1.45	1.15	0.42	7.35	2.69
March	31	0.75	0.45	- -	3.05	- -
April	30	0.37	0.07	- -	0.46	- -
May	31	- -	- -	- -	- -	- -
June	30	- -	- -	- -	- -	- -
July	31	- -	- -	- -	- -	- -
August	31	- -	- -	- -	- -	- -
September	30	- -	- -	- -	- -	- -
October	31	0.20	- -	- -	- -	- -
November	30	0.80	0.50	- -	3.43	- -
December	31	1.25	0.95	0.22	6.75	1.56
				TOTAL —	29.18	7.22

Heating requirements with oil are 29,180 gallons annually, and will decrease to 7,220 gallons in the future.

C. Project III - All equipment operated on purchased electric power. There are no engines and sludge gas will be used for digestion tank heating, with deficiency, if any, made up by purchased oil. Heat of available gas is as follows:

	Winter	Summer
1950 —	1.08×10^6 BTU/hr.	2.44×10^6 BTU/hr.
1970 —	2.39×10^6 BTU/hr.	4.88×10^6 BTU/hr.

Sludge Heating Requirements:

	Winter	Summer
1950 —	0.4×10^6 BTU/hr.	0.36×10^6 BTU/hr.
1970 —	0.67×10^6 BTU/hr.	0.66×10^6 BTU/hr.

Considering space heating requirements, as shown in the other schemes, it is seen that future gas production will more than satisfy both space and sludge demands. For the present, sludge gas will be supplemented by fuel oil in a boiler fired by combination gas and oil burners.

Fuel required for present space heating is computed from table No. 16, page 58.

Table No. 16

Fuel Required for Present Space Heating — Project III

Month	No. of days	Space Heating Require-ments	Sludge Heating Require-ments	Total Heating Require-ments	Available Sludge Gas	Gas Deficiency	Oil Required - 10^3 gals.
		Million BTU/hr.					
January	31	1.45	0.43	1.88	1.08	0.80	5.67
February	28	1.45	0.43	1.88	1.08	0.80	5.12
March	31	0.73	0.41	1.14	1.08	0.06	0.42
April	30	0.37	0.37	0.74	1.08	—	—
May	31	—	0.34	0.34	2.44	—	—
June	30	—	0.37	0.37	2.44	—	—
July	31	—	0.35	0.35	2.44	—	—
August	31	—	0.35	0.35	2.44	—	—
September	30	—	0.37	0.37	2.44	—	—
October	31	0.20	0.35	0.55	1.08	—	—
November	30	0.80	0.39	1.19	1.08	0.11	0.75
December	31	1.25	0.42	1.67	1.08	0.59	4.18

Total - 16.14

Boiler will have 6,750 sq. feet EDR minimum heating surface. Capacity of boiler equals 1,880,000/33,472, or 56.2 boiler H. P. From table No. 16, 16140 Gallons of oil are required annually for space heating.

V. Economic Evaluation of Projects

A large part of the construction cost of a sewage treatment plant involves work below the ground or even below water level, and the cost per m.g.d. capacity for the entire plant may be estimated at $150,000.

Structures will be amortized on a 40 year basis and equipment on a 20 year basis.

The construction costs of the installation under the several projects vary considerably, due to the variations in equipment. Unit prices of the several prinicipal items involved in the various projects have been estimated as follows:

Substructures ....$1.50 per cubic foot

Superstructures .... $0.85 per cubic foot

Motor driven sewage pumps ....$875.00 per M.G.D.

Engine driven sewage pumps ....$2000.00 per M.G.D.

Motor driven blowers .... $3.25 per c.f.m.

Engine generators .... $202.00 per K.V.A.

Electrical work and equipment:

Connected to purchased electric power.. $60.00 per H.P.

Connected to generated electric power.. $50.00 per H.P.

The above unit costs are adapted for manufacturers quotations and from revised cost figures of plants already in operation. Cost data and calculations are found in the appendix, sections 2 to 8.

A. Project 1.

Fixed Charges: Amortization of all equipment will be based on 20 years at 3½%, equivalent to $7.04 per $100 of construction cost. Amortization of structures will be based on 40 years at 3½%, equivalent to $4.62 per $100 of construction cost. The fixed charge rate covers interest and depreciation only, using sinking fund depreciation. The plant is exempted from property and income taxes. Insurance charges will be taken as 1% of the initial investment.

This project, as previously described, contemplates the combined use of sludge gas supplemented by purchased oil to drive dual fuel engine-generators and generate the power requirements. The principal equipment is as follows:

Four sewage pumps of the vertical type, rates as follows: One, 7.5 m.g.d., one, 10 m.g.d., and two, 15 m.g.d.; 35 feet total dynamic head; motor driven by generated current.

Three rotary, positive displacement air blowers, each with a capacity of 3,000 c.f.m. at 7 pounds per square inch pressure, motor driven by generated current.

Three, 300 H.P. dual fuel engine-generators; all auxiliary equipment to be motor operated on generated power.

The ultimate installation would include one additional 15 m.g.d. sewage pump, one 3,000 c.f.m. blower, and one 300 H.P. dual fuel engine-generator.

The general arrangement of the pump and power house, including the above equipment, is shown in plan and section in Figure No. 12-folded insert in back cover.

The cost tabulations are based on the following:

Overall pump and motor efficiency	73%
Blower efficiency	75%
Engine Heat rate	7400 BTU/HP./hr.
Heating boiler efficiency	75%
Heat content of sludge gas	650 BTU/cu.ft.

The estimated construction cost of the pump and blower building under this project may be summarized as follows:

Substructure....273,313 cu. ft. @ $1.50	$410,000.
Superstructure..362,500 cu. ft. @ $0.85	308,000.
Motor driven sewage pumps 47.5 m.g.d. @ $875	41,550.
Motor driven blowers....9,000 c.f.m. @ $3.25	29,250.
Engine-generators... 750 KVA, 0.8 p.f.@ $208........	151,200
Electrical work and equipment	45,000
Piping and valves	100,000
Heating plant	12,420
Contingencies @ 6% of estimated construction cost...	65,800
TOTAL ESTIMATED CONSTRUCTION COST	$1,163,220

Fixed charges for this project are computed as follows: ---

Equipment ......$379,420 @ 0.0704	$26,700
Structures, etc. 783,800 @ 0.0468	36,600
Insurance............... @ 1%	11,632
TOTAL...	$74,932

For the ultimate plant additional equipment will be required for which the initial cost and fixed charges are estimated as follows:

1-Engine-generator —— $50,400 @ 0.0704	....	$3,540.
1-Blower, 2000 c.f.m.- 6,500 @ 0.0704	....	457
1-Sewage pump, 15 m.g.d.-13,120 @ 0.0704	....	923
Insurance	....	49
ADDITIONAL COSTS $70,020	....	$4,969.
INITIAL COSTS........ $1,163,220	....	74,932
TOTALS FOR ULTIMATE PLANT -$1,233,240	....	$79,901.

Annual operating costs for this project may be summarized as follows:

Item	Basis of Design 95,000 Population	Ultimate 180,000 Population
Purchased oil for power....	$8,608	$15,840
Purchased oil for heating..	1,050	———
Labor	39,500	39,500
Maintenance and supplies ..	1,176	1,767
Lubricating oil	653	982
Repair charges	15,000	15,000
ANNUAL OPERATING COST	$65,987	$73,089
FIXED CHARGES	74,932	79,901
TOTAL ANNUAL COST	$140,919	$152,990

B.-Project 11

This project will have the main sewage pumps direct-driven by gas engines using sewage gas which is available. The rest of the power demand of the plant will be furnished by purchased electricity. The principal equipment is as follows:

Four gas engine-driven sewage pumps of the horizontal type, rated as follows: one, 7.5 m.g.d., one, 10 m.g.d., and two 15 m.g.d.; 36 feet total dynamic head.

Three motor-driven rotary, positive displacement air blowers, each with a capacity of 3,000 c.f.m. at 7 pounds per square inch pressure.

The ultimate installation would include one additional 15 m.g.d. gas engine-driven sewage pump and one 8000 c.f.m. blower.

The general arrangement of the pump and power house, including the above equipment, is shown in plan and section in Figure 13-folded insert in back cover.

The cost tabulations are based on the following:

Sewage pump efficiency 78%

Blower efficiency 75%

Gas engine heat rate ... 10,000 BTU/HP/hr.

Heating boiler efficiency 75%

Heat content of sludge gas .... 650 BTU/cu.ft.

The estimated construction cost of the pump and blower building under this project may be summarized as follows:

Substructure	274,455 cu.ft.	@ $1.50.......	$412,000.
Superstructure..................	325,050 cu.ft.	@ $0.85	276,000
Gas engine-driven sewage pumps-47.5 m.g.d.		@$2,000	95,000
Motor-driven blowers.........	9,000 c.f.m.	@ $3.25.......	29,250
Electrical work and equipment			27,000
Piping and valves			100,000
Heating Plant			12,880
Contingencies @ 6% of estimated construction cost			57,130
TOTAL ESTIMATED CONSTRUCTION COST			$1,009,260

Fixed charges for this project are as follows:-

Equipment	$264,130	@ 0.0704	$18,600
Structures, etc. ...	745,130	@ 0.0468	34,850
Insurance		@ 1%	10,093
		TOTAL	$63,543

For the ultimate plant, additional equipment will be required for which the initial cost and fixed charges are estimated as follows:-

1- Blower, 2,000 c.f.m.............$6,500 @ 0.0704..		$457.
1- Gas engine-driven sewage pump- 15 m.g.d. $30,000 @ 0.0704..		2,112
Insurance		26
ADDITIONAL COSTS	$36,500	$2,595
INITIAL COSTS	$1,009,260	63,543
TOTALS FOR ULTIMATE PLANT	$1,045,760	$66,138

Annual operating costs for this project may be summarized as follows:

Item	Basis of Design 90,000 Population	Ultimate 160,000 Population
Purchased oil for heating	$2,334	$578
Labor	39,500	$39,500
Maintenance and supplies	199	395
Lubricating oil	110	219
Repair charges	10,000	10,000
Purchased electricity	21,493	36,047
ANNUAL OPERATING COST	$73,636	$86,739
FIXED CHARGES	63,543	66,138
TOTAL ANNUAL COST	$137,179	$152,877

C-Project III

This project contemplates the use of purchased power for driving all equipment. Sludge gas will be available for building and digestion tank heating requirements supplemented, in part, with purchased oil. The principal equipment is as follows:

Four, motor-driven sewage pumps of the vertical type, rated as follows: One, 7.5 m.g.d., one, 10 m.g.d., and two, 15 m.g.d.; 35 feet total dynamic head.

Three motor-driven rotary, positive displacement air blowers, each with a capacity of 3,000 c.f.m. at 7 pounds per square inch pressure.

The ultimate installation would include one additional 15 m.g.d. sewage pump and one 2,000 c.f.m. blower.

The general arrangement of the pump and the power house, including the above equipment, is shown in plan and section in Figure No. 14. - folded insert in back cover.

The cost tabulations are based on the following:-

Overall pump and motor efficiency....... 73%

Blower efficiency........................ 75%

Engine heat rate .... 7,400 BTU/HP-hr.

Heating boiler efficiency................ 75%

Heat content of sludge gas.............. 650 BTU/cu.ft.

The estimated construction cost of the pump and blower building under project may be summarized as follows:

Substructure	250,875 cu.ft.	@ $1.50		$376,000
Superstructure	313,140 cu.ft.	@ $0.85		266,170
Motor-driven sewage pumps	47.5 m.g.d.	@ $875		41,550
Motor-driven blowers	9,000 c.f.m.	@ $3.25		29,250
Electrical work and equipment				54,000
Piping and valves				100,000
Heating Plant				13,800
Contingencies @ 6% of estimated construction cost				52,550
TOTAL ESTIMATED CONSTRUCTION COST				$933,320

Fixed charges for this project are as follows:

Equipment	$238,600	@ 0.0704	$16,820
Structures, etc.	694,700	@ 0.0468	32,500
Insurance		@ 1%	9,333
	TOTAL		$58,653

For the ultimate plant, additional equipment will be required for which the initial cost and fixed charges are estimated as follows:-

1-Blower, 2,000 c.f.m.	$6,500	@ 0.0704	$457.
1-Sewage Pump, - 15 m.g.d.	$13,180	@ 0.0704	923.
Insurance			14.
Additional Costs	$19,680		$1,394.
INITIAL COSTS	$933,320		58,653.
TOTALS FOR ULTIMATE PLANT	$952,940		$60,047.

Annual operating costs for this project may be summarized as follows:-

Item	Basis of Design 90,000 Population	Ultimate 180,000 Population
Purchased oil for heating	$1,291	———
Labor	31,100	$31,100
Maintenance, supplies, lubricating oil	1,520	2,130
Repairs	7,000	7,000
Purchased electricity	32,670	51,146
ANNUAL OPERATING COST	$73,581	$91,376
FIXED CHARGES	58,653	60,047
TOTAL ANNUAL COST	$132,234	$151,423

Table No. 17

SUMMARY of ESTIMATED CONSTRUCTION, OPERATING and TOTAL ANNUAL COSTS

Item	Project 1	Project 11	Project 111
		Construction Cost	
Substructure	$410,000	$412,000	$376,000
Superstructure...........	308,000	276,000	266,170
Motor-Driven Sewage Pumps	41,550	———	41,550
Engine-Driven Sewage Pumps	———	95,000	———
Motor-Driven Blowers	29,250	29,250	29,250
Engine-Generators	151,200	———	———
Electrical Work and Equipment	45,000	37,000	54,000
Piping and Valves	100,000	100,000	100,000
Heating Plant	12,420	12,880	13,800
Contingencies	65,800	57,130	52,550
TOTAL CONSTRUCTION COSTS. BASIS OF DESIGN......	$1,163,220	$1,009,260	$933,320
ADDITIONAL FOR ULTIMATE PLANT	70,020	36,500	19,620
TOTAL CONSTRUCTION COST ULTIMATE.............	$1,233,240	$1,045,760	$952,940
		Fixed Charges	
BASIS OF DESIGN.......	$ 74,932	$63,545	$56,663
ULTIMATE	79,901	66,136	60,047

Table No. 17 (Continued)

Item	Project 1	Project 11	Project 111
Operating and Total Annual Costs----Basis of Design			
Purchased Electric Power..	----	21,493	32,670
Purchased Oil for Power...	8,608	------	----
Purchased Oil for Heating.	1,050	2,334	1,291
Labor	39,500	39,500	31,100
Maintenance, Supplies, Repairs, etc.........	16,829	10,309	8,520
ANNUAL OPERATING COST	$65,987	$73,636	$73,581
TOTAL ANNUAL COST	140,919	137,179	132,234
Operating and Total Annual Costs--Ultimate			
Purchased Electric Power..	------	36,047	51,146
Purchased Oil for Power...	15,840	-------	------
Purchased Oil for Heating	-------	578	------
Labor	39,500	39,500	31,100
Maintenance, Supplies, Repairs, etc........	17,749	10,614	9,130
ANNUAL OPERATING COST.....	$73,089	$86,739	$91,376
TOTAL ANNUAL COST	152,990	152,877	151,423

VI. Conclusions

A. Discussion of Economic Evaluation.

It is determined by reference to Table No. 17 that purchasing all power requirements is the least expensive of the three schemes. Therefore, the economic selection for the plant considered is the purchased power project where both construction and total annual costs are lowest.

The generation proposals necessarily involve higher construction costs for the power plant because of the additional equipment and larger building space which must be provided. If, therefore, partial or complete generation of power requirements is to merit consideration, the total annual costs would have to be less than purchased power. In addition, a justifiable return on the additional investment should be presented.

It must be recognized, however, that the studies made are valid only for the particular conditions considered and prevailing. Since conditions vary depending on location, a similar analysis made with other considerations might yield a different result. Also for a larger plant, having a higher ratio of available gas to power requirements, the decision might favor generation. A more unfavorable rate than is offered by the Consolidated Edison Co. of New York could easily change the complexion of the preceding analysis. Electric rates must, however, be credited with 11½%, for example, which is returned to the City of New York as taxes. The importance of the downward trend of electric power rates further places the issue in favor of purchased power.

However, the use of engines and generation of power makes possible a more complete utilization of gas, which is a by-product of the sewage treatment process. The savings derived from the operation of a larger plant than the one considered, may make possible a higher grade of sewage treatment for the same cost, for example, activated sludge as compared with sedimentation.

Regardless of the source of power requirements, the sanitary benefits derived from the digestion of sludge are not to be de-emphasized. The future policy of New York City's treatment will be to discard offensive non-digestion sewage treatment plants. The availability of a high grade fuel obtained from the digestion of the sludge emphasizes the necessity for performing an economic analysis to determine the merits of self-generation of power requirements.

B. Discussion of Intangible Factors

In the foregoing only factors upon which a monetary value can be placed have been considered. There are a number of intangible factors having a bearing upon the selection of the type of equipment and power to be used. The more important of these items are as follows:-

1. Convenience of motor driven pumps.

2. Flexibility of operation of engine-driven blowers, particularly the rotary positive displacement type.

3. Limitation of flexibility of operation of motor-driven blowers.

4. Disadvantages of motor-driven blowers where gas engine generators are used from the standpoint of starting load.

5. Advantages of self-contained power source at the plant versus outside power source.

6. Policy as to development and use of all potential power.

Regarding flexibility of operation, engine-generators are to be favored as compared with blowers or pumps direct-connected to engines. All plant equipment can be driven by the engine-generators and the engines can be all of the same size and fewer in number. The overhauling and repairs of any generator unit will not disturb the normal operation of the plant. This advantage frequently compensates for the increased efficiency gained by eliminating electrical losses between an engine and a pump or blower, amounting to about 15 per cent of the power developed by the engine.

If the pumps and blowers are direct connected to engines, each engine must be suitable for its driven unit, and are often of different sizes. If the engine breaks down or requires inspection and overhaul, the entire unit becomes idle. More spare parts must be carried in stock and usually more floor space is needed to accommodate the larger number of engines. A combination of direct-engine driven blowers with all other equipment electrically operated is often adopted since blowers usually absorb about 50 per cent of the entire plant load at average flow and are a fairly constant load.

Selection of the number of engine-generators to be used requires careful consideration. Though it may be more economical to use two or three large capacity engines, reliability, convenience and cost of operation may favor a larger number of smaller engines. This avoids interruption of plant operation where, say, one unit is being overhauled and another breaks down unexpectedly. It also avoids placing a large capacity engine in service for slight increase in plant load.

Another factor that must be considered in designing the power set-up is that when a new plant is started up, considerable time elapses before gas is produced in sufficient quantities for operating the engines. If gas engines are used, during the interim, it will be necessary to purchase utility gas. The cost of gas and gas facilities is an important consideration. Dual fuel engines permit complete operation on diesel oil as well as any combination of gas and oil and, as such, have a distinct advantage on this respect.

C. Closure

I have attempted to present an analysis of the engineering and economic decisions which are involved in a power study for a sewage treatment plant. Since this study was made for a hypothetical plant, not yet designed, certain simplifying assumptions were necessary in the approach to this problem which will not ordinarily have to be made. The results of this thesis, as has been emphasized, are not to be taken as absolute, but rather as a solution obtained from conditions considered.

It is hoped that similar economic analyses will be made for other sewage treatment plants and that this paper will be a guide in that direction.

- A P P E N D I X -

Section 1- Calculation of Power Requirements.

Blower delivery-(c.f.m.)---average flows:

Present		Future	
Winter	Summer	Winter	Summer
$\frac{0.5 \text{ cu.ft.air} \times 10{,}000{,}000 \text{ gal/day}}{\text{gal. sewage} \; 24 \times 60 \text{ min. day}}$ = 3470 c.f.m.	5,205	6,940	10,410

Take 75% blower efficiency (rotary positive displacement blowers).

$$\text{Head} = 7 \text{ p.s.i.} \times 144 \frac{\text{in}^2}{\text{ft}^2} \times \frac{\text{cu.ft.}}{0.0751 \text{ lb.}} = 13{,}420 \text{ ft. of air}$$

$$\text{H.P.} = \frac{3470 \times 0.0751 \times 13420}{0.75 \times 33000} = 141 \text{ H.P.} = 105 \text{ kw. for average present winter flow}$$

$$\text{H.P.} = \frac{5205 \times 0.0751 \times 13420}{0.75 \times 33000} = 212 \text{ H.P.} = 158 \text{ kw. for average present summer flow}$$

$$\text{H.P.} = \frac{6940 \times 0.0751 \times 13420}{0.75 \times 33000} = 284 \text{ H.P.} = 212 \text{ kw. for average future winter flow}$$

$$\text{H.P.} = \frac{10410 \times 0.0751 \times 13420}{0.75 \times 33000} = 425 \text{ H.P.} = 317 \text{ kw. for average future summer flow}$$

Pumping kw.: Average Flow

1) winter-present, flow = 10 m.g.d.

take overall efficiency = 73%

$$\text{average flow} = 10^7 \times \frac{1}{7.48} \times \frac{1}{24} \times \frac{1}{60} \times 62.4 = 58{,}000 \text{ lb./min.}$$

$$\text{H.P.} = \frac{58000 \times 35}{0.73 \times 33000} = 84.3 \text{ H.P.} = 63 \text{ kw.}$$

2) summer-present, flow = 15 m.g.d.

take overall efficiency = 74%

average flow = 87,000 lb./min.

$$\text{H.P.} = \frac{87000 \times 35}{0.74 \times 33000} = 124.8 \text{ H.P.} = 93 \text{ kw.}$$

3) winter-future, flow = 20 m.g.d.

take overall efficiency = 74%

average flow = 116,000 lb./min.

$$\text{H.P.} = \frac{116000 \times 35}{0.74 \times 33000} = 166 \text{ H.P.} = 124 \text{ kw.}$$

4) summer-future, flow = 30 m.g.d.

take overall efficiency = 74%

average flow = 174,000 lb./min.

$$\text{H.P.} = \frac{174000 \times 35}{0.74 \times 33000} = 240 \text{ H.P.} = 186 \text{ kw.}$$

The results of the above calculations, as well as those for minimum and maximum flows, are found in table No. 2, Page 20.

Section 3-Table of Unit Construction Costs of Various Plants

Electrical Work and Equipment

Plant	Year Built	Installed H.P.	Low Bid	Cost per Installed H.P.
Buffalo Main Pumping Station	1936	4050	$107,000	$26.40
Buffalo Pumping Station	1937	350	13,490	38.50

Electrical work and equipment consists of the following:

1) underground duct and conduit system
2) conduits and supports, boxes, and fittings
3) wire and cable
4) main switchboard and benchboard
5) panel and control cubicles
6) transformers
7) motor-generator sets
8) storage batteries
9) lighting fixtures

Motor-Driven Sewage Pumps

Plant	Year Built	Capacity M.G.D.	Installed H.P.	Low Bid	Cost per M.G.D.	Cost per Installed H.P.
Buffalo Main P.S.	1936	720	4050	$325,000	$452	$80.20
Buffalo P.S.	1937	112	350	35,240	315	100.50

Motor-Driven Blowers

Plant	Year Built	Capacity C.F.M.	Installed H.P.	Low Bid	Cost per C.F.M.	Cost per installed H.P.
Peoria, Ill.	1929	35,000	1,575	$35,563	$1.02	$22.60
Wards Island, New York City	1936	226,000	12,000	368,510	1.63	30.71

Engine-Generators

Plant	Year Built	Capacity Kw.	K.V.A.	Low Bid	Cost per kw.	Cost per K.V.A.
Toledo	1939	600	750	$80,000	$133	$107

Engine-Driven Sewage Pumps

Plant	Year Built	Capacity M.G.D.	Installed H.P.	Total Cost	Cost per M.G.D.	Cost per Installed H.P.
Tallmans Is. N.Y.C.	1939	100	1,080	$151,808	$1,518	$140.56

Engine-Driven Blowers

Plant	Year Built	Capacity C.F.M.	Installed H.P.	Low BID	Cost per C.F.M.	Cost per Installed H.P.
Tallmans Is., N.Y.C.	1939	60,000	2,500	$316,677	$5.28	$126.67

Mechanical Equipment

Plant	Year Built	Pumping Capacity M.G.D.	Low Bid	Cost per M.G.D.
Tallmans Is.	1939	100	137,608	$1,376
Wards Is.	1936	540	498,854	924

Substructure

Plant	Year Built	Cubic Feet	Total Cost	Unit Cost
Tallmans Is.	1939	655,900	$487,980	$ 0.744 per cu.ft.

SUPERSTRUCTURE

Plant	Year Built	Cubic Feet	Total Cost	Unit Cost
Tallmans Island	1939	929,650	$411,585	$0.443 per cu.ft.

Engine-driven equipment costs: Costs of engine-driven equipment were obtained from manufacturers. The breakdown of the engine-generator installation under Project 1 is as follows:

Engines :	3 - 300 H.P. @ $36,000	$108,000
Spare parts:	5% x $108,000..........	5,400
Auxiliaries:	25% x $108,000.........	27,000
Piping:	$12.00/H.P. x 900.....	10,800
		$151,200

Section 3 - Labor Costs

Labor costs are one item of operation of the pump and power house installation. Under Projects 1 and 2, the following personnel, based on three-watch operation are considered essential, with annual salaries including fringe benefits, such as pension, social security, unemployment insurance, etc:

1-	Chief Engineer	Diesel	@ $4700	$4700
4-	Assistant Engineers	Diesel	@ $3800	15200
7-	Oilers and Laborers		@ $2800	19600
			TOTAL	$39,500

For Project 3:

2-Stationary Engineers	Electric	@ $4400	$8800
3-Assistant Engineers	Electric	@ $3700	11100
4-Laborers		@ $2800	11200
		Total	$31,100

Section 4 - Maintenance, Supply and Repair Costs

These charges will vary with the size of the engine installation. For purposes of this study, the costs of such items in many operating Diesel engine plants for 1942 have been reviewed and are summarized in Table No. 1-A.

Charges for these items are essentially matters of judgment as published data show wide variation among plants of similar size. Study of more recent available A.S.M.E. reports indicate the following as reasonable charges for engine installations:

Maintenance	$0.0002 per K.W.H.
Supplies........................	$0.0001 per K.W.H.
Lubricating Oil.................	1 Gallon per 3000 K.W.H. @ $0.50 Gal.

Repair charges will be taken as $15,000 per year for Project 1 and $10,000 per year for Project 2.

Similar costs for electrically-driven equipment are difficult to obtain and are relatively small in amount. Data for plants of the Chicago Sanitary District are summarized in Table No. 2-A. For purposes of this study, for purchased power installations, as Project 3, a value of $0.0005 per K.W.H. has been taken for maintenance and supplies, and $7,000 per year for repairs.

Project 1-Normal operation-present = 2,300 H.P. engines

Normal operation-future = 3,300 H.P. engines

Present power load = 600 H.P. x 0.746 x 24 x 365 = 3,920,000 kw-hrs/yr.

Costs:

Maintenance and Supplies = 0.0003 x 3,920,000 = $1176/yr.

Lubricating Oil = 1 gal. 3000 kw.hrs. x 3,920,000 x $0.50 = $653.yr.

Repair charges .... $15,000/yr.

Future power load = 900 H.P. x 0.746 x 24 x 365 = 5,890,000 kw-hrs/yr.

Costs:

Maintenance and Supplies = 0.0003 x 5,890,000 = $1767/yr.
Lubricating oil = 1 gal/3000 kw.hrs. x 5,890,000 x $0.50 = $982./yr.
Repair charges .... $15,000./yr.

Project 11-Normal operation-present = winter - 63 kw.
summer - 93 kw.

Normal operation-future = winter - 124 kw.
summer - 186 kw.

Present power load = (63 x 24 x 212) + (93 x 24,153) = 662,000 kw.-hrs./yr.

Costs:

Maintenance and Supplies = 0.0003 x 662,000 = $199./yr.

Lubricating oil = 1 gal/3000 kw.hrs. x 662,000 x $0.50 = $110/yr.

Repair charges .... $10,000/yr.

Future power load = (124 x 24 x 212) + (186 x 24 x 153) = 1,315,000 kw.-hrs./yr.

Maintenance and Supplies = 0.003 x 1,315,000 = $395./yr.
Lubricating oil = 1/3000 x 1,315,000 x $0.50 = $219./yr.
Repair charges ....$10,000./yr.

Table No. 1-A

Maintenance, Supply and Repair Costs for Oil Engines - 1942 from A.S.M.E. Report on Oil Engine Power Cost.

Installed H.P.	Cost per K.W.H.
10,000	$0.00087
9,000	0.00089
8,000	0.00090
7,000	0.00091
6,000	0.00092
5,000	0.00098
4,000	0.00102
3,000	0.00114
2,000	0.00134
1,500	0.00155
1,000	0.00197
900	0.00214
800	0.00235
700	0.00263
600	0.00300
500	0.00360
400	0.00452
300	0.00650

Table No. 2-A

Maintenance, Supply and Repair Costs for Motor-Driven Equipment (Data taken from cost records of the Chicago Sanitary District)

	Period of Records (4 yrs)	Installed H.P.	Millions of K.W.H. (total)	Total Costs	Cost per K.W.H.
North Side	1938-1941	18,190	122.012	$52,507	$0.000427
Calumet...	1939-1941	9,572	51.907	6,756	0.000130
West Side.	1938-1941	12,300	150.745	38,541	0.000257
Average	4 years	13,354	108.221	$32,601	$0.000301

Section 5 - Electrical Energy Costs

In computing electrical energy costs, the Consolidated Edison Co. of New York's Service Classification No. 2-General rate will be used. This is as follows:

1st 10 K.W.-hr. or less		$0.75
70	@	0.055
320	@	0.050
1,100	@	0.040
3,500	@	0.025
5,000	@	0.019
5,000	@	0.015
5,000	@	0.013
60,000	@	0.009
170,000	@	0.008
over 25,000	@	0.005
		less 10%

Demand:

1st 5 K.W.		0.
Next 20 K.W.	@	$2.50/K.W.
75 K.W.	@	2.00/K.W.
900 K.W.	@	1.50/K.W.
over 1000	@	1.00/K.W.
		less 10%

Project 3 - All purchased electricity (present)

Present average demand - winter = 208 kw.- for 7 months

- summer = 311 kw.- for 5 months

Energy-winter = 208 kw. x 24 x 30 = 200,000 K.W.H. per month

-summer = 311 kw. x 24 x 30 = 224,000 K.W.H. per month

Energy charge-winter = (10 x $0.75) + (70 x $0.055) + (320 x $0.050)
+ (1100 x $0.04) + (3500 x $0.025)
+ (5000 x $0.019) + (5000 x $0.015)
+ (5000 x $0.012) + (60000 x $0.009)
+ (120000 x $0.008) + (200000 x $0.003)

= $2,488.85 x 7 mo.

= $17,421.95 Less 10%

Energy charge - summer = $2488.85 + (24,000 x $0.011)

= $2752.85 x 5 mo.

= $13764.25 less 10%

Demand charge - winter = (5 x 0) + (20 x $2.50) + (75 x $2.00) + (108 x $1.50)

= $2534 less 10%

Demand charge - summer = $200 + (211 x $1.50)

= $2,580 less 10%

Total charge with all purchased electricity (present) =

$17,422 + $13,764 + $2,534 + $2,580

= $36,300 Less 10%

= $32,670

Project 3 - All purchased electricity (future)

Future average demand-winter = 416 kw. for 7 months

-summer = 623 kw. for 5 months

Energy-winter = 416 kw. x 24 x 30 = 300,000 K.W.H. per month

-summer = 623 kw. x 24 x 30 = 448,000 K.W.H. per month

Energy charge -winter = $7.50 + $3.85 + $16.00 + $44.00 + $87.50 + $95.00 + $75.00 + $60.00 + $540.00 + (170,000 x $0.008) + (80,000 x $0.005) + (300,000 x $0.005)

= $3,438.85 x 7 mo.

= $24,071.95 less 10%

Energy charge-summer = $3,438.85 + (148,000 x $0.008)

= $4,622.85 x 5 mo.

= $23,114.25 Less 10%

Demand charge-winter = $200 + (316 x $1.50)

= $674 x 7 mo.

= $4,718 less 10%

Demand charge-summer = $200 + (523 x $1.50)

= $985 x 5 mo.

= $4,925 less 10%

Total charge with all purchased electricity (future) =

$24,072 + $23,114 + $4,718 + $4,925

= $56,829 Less 10%

= $51,146

Project 2-Everything except engine-driven pumps on purchased electricity. (Present)

Present average demand-winter = 145 kw. for 7 months

-summer = 218 kw. for 5 months

Energy-winter-145 kw. x 24 x 30 = 104,800 KWH. per mo.

-summer-218 kw. x 24 x 30 = 157,000 KWH. per mo.

Energy charge-winter = $7.50 + $3.85 + $16. + $44 + $87.50 + $95 + $75 + $60 + $540. + (24,200 x $0.008) + (104,800 x $0.008)

= $1,435.05 x 7 mo.

= $10,045.35 less 10%

Energy charge-summer = $1,435.05 + (52,800 x $0.011)

= $2,015.85 x 5 mo.

= $10,079.25 less 10%

Demand charge-winter = 5 x 0 + (20 x $2.50) + (75 x $2.00) + (45x $1.50)

= $267.50 x 7 mo.

= $1,872.50 less 10%

Demand charge-summer = $200 + (118 x $1.50)

= $377 x 5 mo.

= $1,885 less 10%

Total Charge (present) = $10,045 + $10,079 + $1,872 + $1,885

= $23,881 less 10%

= $21,493

Project 2 - Everything except engine-driven pumps on purchased electricity. (future)

Future average demand - winter = 292 kw. for 7 months

- summer = 437 kw. for 5 months

Energy-winter = 292 x 24 x 30 = 210,240 K.W.H. per month

summer = 437 x 24 x 30 = 314,640 K.W.H. per month

Energy charge-winter = \$7.50 + \$3.85 + \$16. + \$44. + \$87.50 + \$95 + \$75 + \$60. + \$540. + (130,240 x \$0.011)

= \$2,361.50 x 7 months

= \$16,530.50 less 10%

Energy charge-summer = \$2,361.50 + (39,760 x \$0.011) + (64,640 x \$0.008)

= \$3,316 x 5 months

= \$16,580 less 10%

Demand charge-winter = \$200 + (192 x \$1.50)

= \$488 x 7 months

= \$3,416 less 10%

Demand charge-summer = \$200 + (337 x \$1.50)

= \$705 x 5 months

= \$3,525 less 10%

Total charge purchasing part of power demand (future)

= \$16,531 + \$16,580 + \$3,416 + \$3,525

= \$40,052 less 10%

= \$36,047

Section 6 - Cost of Fuel Oil

Diesel oil requirement for pilot oil, and to supplement sludge gas as engine fuel, are computed as follows for project 1:

Present

Engine fuel consumption = 74,400 gal. annually @ 7,400 BTU/HP-hr. heat rate

Pilot oil-6% of total = 444 BTU/HP.hr.

Heat content of oil = 142,700 BTU/gal.

Cost of oil = $0.095/gal.

Normal operation = 2-300 HP engines.

Therefore, pilot oil = $\frac{600 \times 444}{142,700}$ = 1.865 gal./engine-hr.

Total pilot oil cost = 1.865 x 24 x 365 x $0.095 = $1,548.

Fuel oil Cost = 74,400 x $0.095 = $7,060

Total power oil cost = $8,608

Future

Engine fuel consumption = 142,300 gal. annually @ 7,400 BTU/HP-hr. heat rate

Normal future operation = 3-300 H.P. engines

Pilot oil = $\frac{900 \times 444}{142,700}$ = 2.80 gal./engine-hr.

Total pilot oil cost = 2.80 x 24 x 365 x $0.095 = $2,330

Fuel oil cost = 142,300 x $0.095 $13,510

Total power Oil cost $15,840

Bibliography

1. Metcalf and Eddy, American Sewerage Practice, Vols. I, II, III
   Mc Graw Hill (1935)

2. Keefer, Sewage Treatment Works,
   Mc Graw Hill (1940)

3. Ehlers and Steel, Municipal and Rural Sanitation,
   Mc Graw Hill (1937)

4. Babbitt, Sewerage and Sewage Treatment
   John Wiley & Sons (1947)

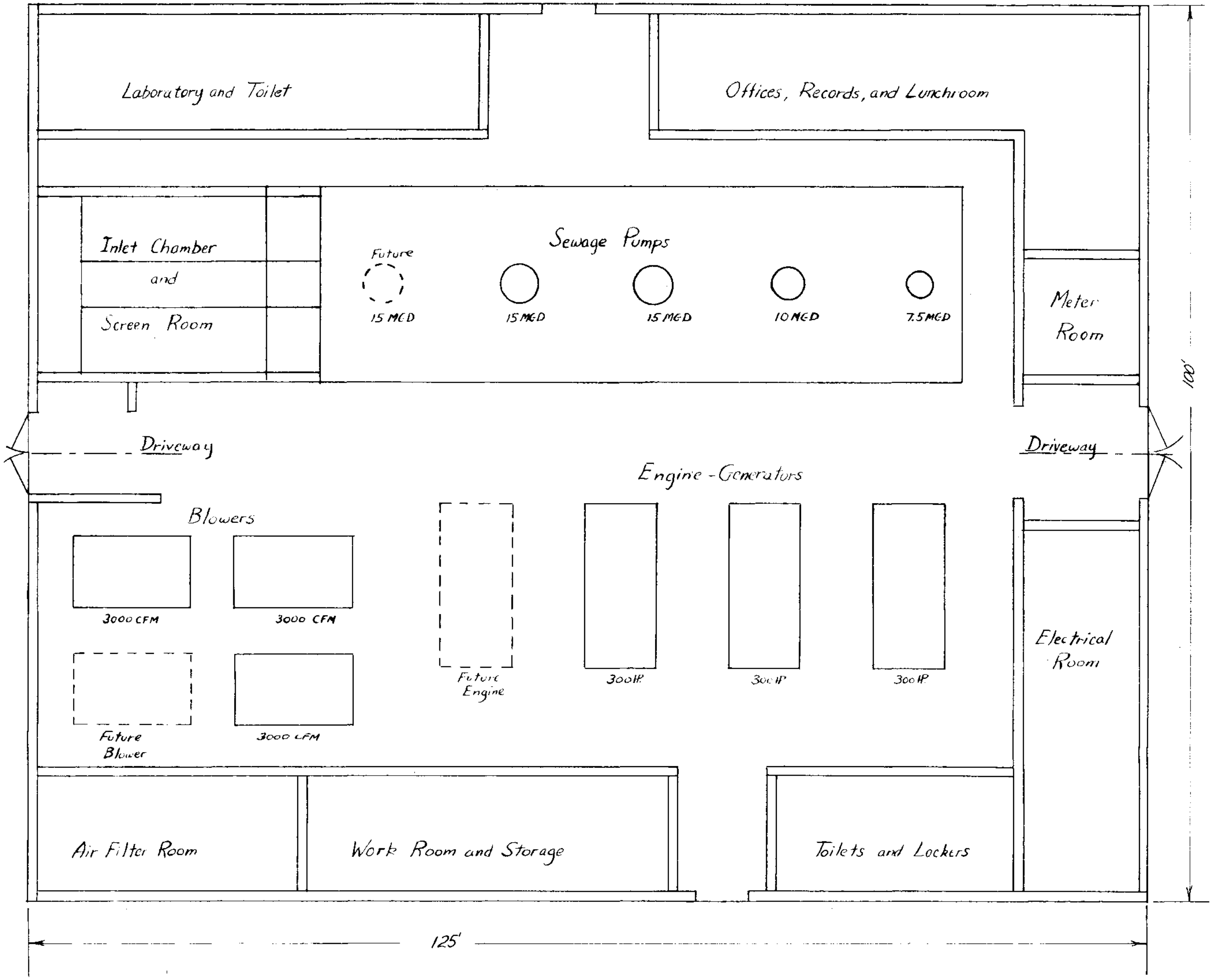
5. Babbitt and Doland, Water Supply Engineering,
   Mc Graw Hill (1949)

6. Imhoff and Fair, Sewage Treatment,
   John Wiley and Sons (1940)

7. Steel, Water Supply and Sewerage,
   Mc Graw Hill (1947)

8. Woods and De Garmo, Engineering Economy
   The Macmillan Company (1948)

9. Handy, Public Utility Construction Cost Indexes and Financial and Operating Ratios,
   Whitman Requardt and Associates (1950)



Plan: Scale 1" = 10'-0"

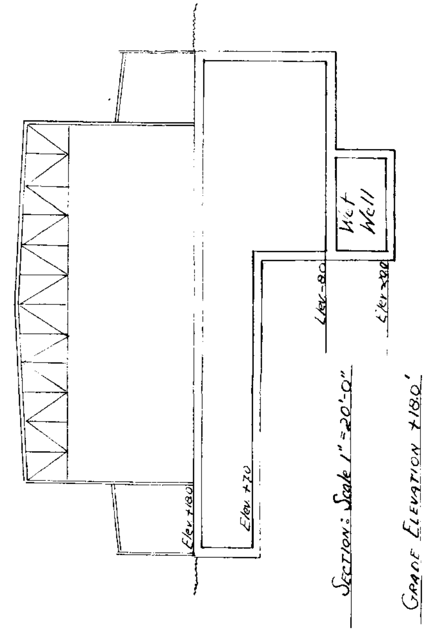
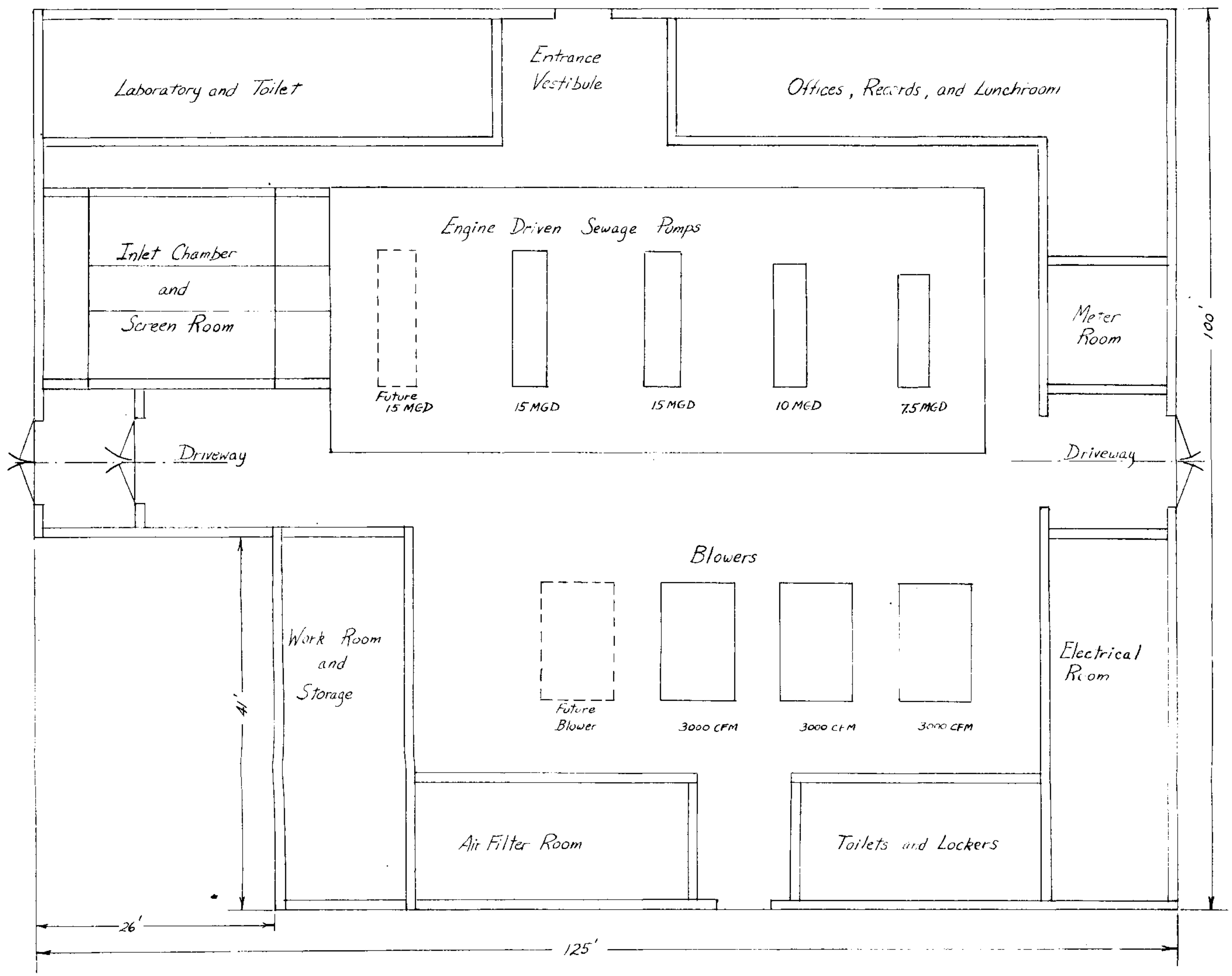


Figure No. 12

Pump and Power House Layout - Project I

- For Estimating Building Volume

and Floor Space



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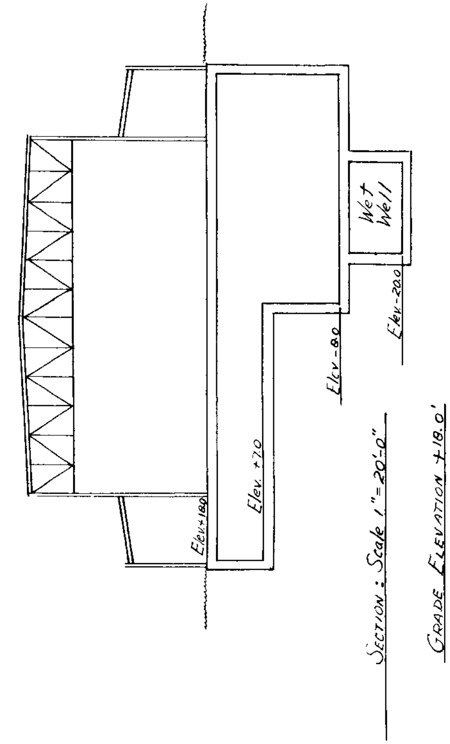

Figure No. 13
Pump and Power House Layout – Project II
– For Estimating Building Volume
and Floor Space

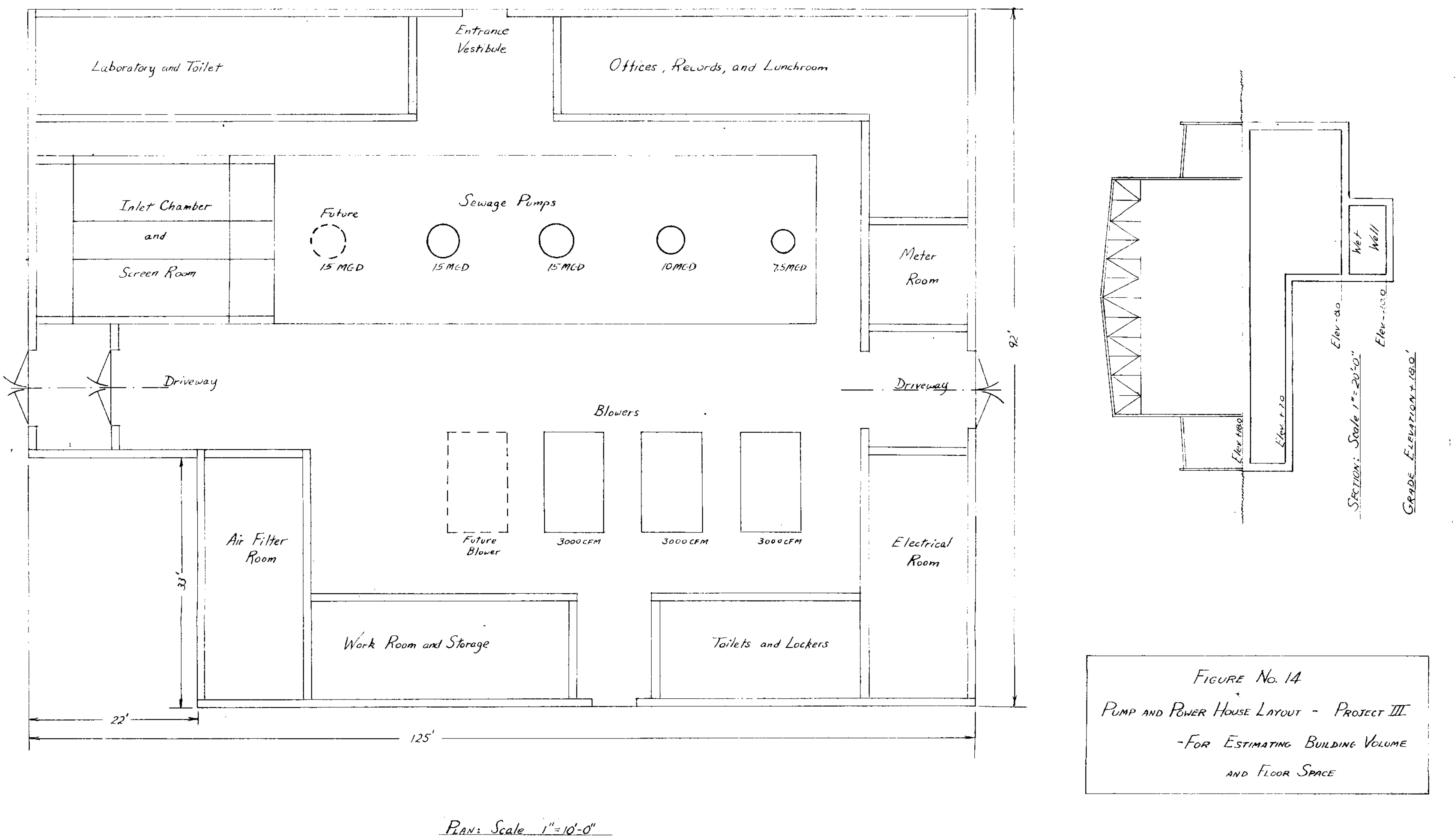

Figure No. 14
Pump and Power House Layout - Project III
-For Estimating Building Volume and Floor Space