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EVALUATION OF POTENTIAL MILITARY APPLICATIONS OF STIRLING ENGINES

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July 1988

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This paper reports on the potential military applications of the Stirling engine. In the applications considered here, the major advantages cited for the Stirling engine are multifuel capability, efficiency, and low noise levels. These potential advantages are small compared to current diesels. Diesels are already able to burn broadcut fuels, have high efficiency, and can be adequately muffled. Their major disadvantages are size, weight, and cost. These disadvantages are only severe in vehicular and mobile power applications where the competition is open-cycle internal combustion engines (diesel, spark-ignition, or turbine). In underwater and space power applications where closed-cycle engines are a necessity, the use of Stirling engines shows more promise.

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INSTITUTE FOR DEFENSE ANALYSES

PREFACE

This report was prepared for Dr. Donald Dix, Staff Specialist for Propulsion, in OUSD(R&AT) under contract number MDA 903 84C 0031, Task Order T-D6-570, Relative Assessment of Technology Payoffs. It represents a quick-reaction (three-month) response to a request to provide material and analyses which would allow DoD to define its position on the development and use of Stirling engines for military purposes.

Many thanks are due to Mr. Donald Weidhuner and Mr. Raymond Standahar, who are IDA consultants, both for assisting in the initial organization of the study and for reviewing the final report. Dr. Karen J. Richter of our staff also reviewed the final report. Mr. J. Scott Hauger, president of Applied Concepts, was extremely helpful in preparing, on short notice, a summary report of the current state-of-the-art in Stirling engine development. Appendix B is extracted from this summary report.

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EXECUTIVE SUMMARY

A. OVERVIEW

This paper reports on the potential application of Stirling engines to military missions. The Stirling engine is a closed-cycle heat engine with potentially high efficiency which is capable of operating from a variety of heat sources and fuels. Other advantages cited are clean burning and low emissions, low noise and vibration, and high reliability. These characteristics were evaluated in comparison with the competing engines currently used or being developed by the military in six applications—generator sets, remotely piloted underwater vehicles, non-combat vehicles, combat vehicles, auxiliary power units, and space power. Each of these applications requires a different set of engine characteristics, and in each case there are other power sources that compete with the Stirling engine's capabilities.

There are two types of Stirling engines to be considered--the "kinematic" engine and the "free-piston" engine. Most of the military missions would use the kinematic Stirling that produces mechanical work directly; and this is the one that has received nearly all the development work to date. The free-piston Stirling is a sealed engine which uses a magnetized power piston to activate alternator coils outside the pressure walls of the engine, thus producing an electrical output. This configuration avoids the working fluid leakage problems associated with the moving seals in a kinematic engine, but may be somewhat less efficient.

B. CURRENT STATUS OF THE STIRLING ENGINE

The characteristics of current kinematic Stirling engines are shown in Table ES-1. The SPS V160 is a Swedish engine and is the only Stirling engine that has been built in any quantity. The others are experimental engines that have been developed in order to demonstrate the Stirling engine capabilities in a working device. The MTI Mod I, I+, and II engines were developed for automotive applications under a Department of Energy program.

ES-1

Table ES-1. US Kinematic Stirling Engine State of the Art

Firm	Model	Number Built	Operating Hours	Power (kW)	@RPM	Working Gas
MTI	Mod I	4	*	54	4,000	hydrogen
MTI	Mod I+	7	18,600	58	4,000	hydrogen
MTI	Mod II	2	800	60	4,000	hydrogen
STM	STM4-120	2	100	25	1,800	helium
SPS	V160	130	340,000	15	1,800	helium

* Included in Mod I+

Firm	Model	Number Pistons/ Volume per Piston (cc)	Hot Temp. (deg C)	Maximum Pressure (MPa)	Power Density (kg/kW)	Max. Thermal Efficiency	Mean Time Between Failures
MTI	Mod I	4/123	720	15	6.7	35%	15
MTI	Mod I+	4/125	820	15	6.1	37%	50
MTI	Mod II	4/120	820	15	3.7	40%	--
STM	STM4-120	4/120	812	13	6.7	45%	--
SPS	V160	1/160	720	15	6.7	28%	3,000

Note: All information is as provided by manufacturers.

In many of the comparisons that follow, the competitive engines are internal combustion engines. These can be diesel or spark ignition piston engines or gas turbine engines. In making comparisons between these engines and the Stirling it must be realized that all of the internal combustion engines have been in practical use for many years and their performance and cost at a given size can be accurately predicted. It is more difficult to make such projections for the Stirling. The Stirling engine with the most performance data is the SPS V160. Unfortunately, it is an older design and is considerably heavier than more recently developed MTI engines. To cast the Stirling in the best possible light in the following evaluations, performance estimates include values scaled from the MTI Mod II data, which is the lightest kinematic Stirling yet developed.

For size and weight, it is assumed that Stirlings scale roughly like diesels. Cooling requirements have been estimated by doubling diesel requirements. The potential for uprating Stirlings is estimated to be very limited because current Stirlings are already operating at pressures and speeds that other engines find stressing. Since comparisons are made with more conservative designs of other engines, this again puts the Stirling in the best possible light insofar as size and weight are concerned.

ES-2

In each of the sections that follow, two questions will be addressed. (1) *If* Stirling engines were commercially available, are there places where the Department of Defense might use them? The criterion used for this evaluation is whether Stirling engines are competitive with other alternatives in terms of performance, size, and cost. (2) Is there a military application that warrants Department of Defense support of Stirling engine development? The evaluation criterion here is whether there are unique military advantages that could be attained by using the special characteristics of the Stirling engine. In general, if a large commercial market exists, government support of development is not necessary. It is generally DoD policy to support development of engines only if the potential *military* advantage is large enough to offset the development costs.

C. GENERATOR SETS (MOBILE ELECTRIC POWER)

1. General Purpose Sets

There are a wide variety of military needs for portable generation of electric power to support weapons systems, communications, housekeeping power, environmental control, and many other functions. In order to avoid proliferation of makes, models, and sizes, a DoD Standard Family of Mobile Electric Power Sets has been established from which all users of electric power in the field must choose to support their system requirements. This family is shown in Table ES-2. It will be noted that while the power range is 0.5 to 750 kilowatts (kw), the majority of sets are in the 1.5 to 60 kw range, with the smaller end of the range (under 15 kw) being most numerous. With the exception of the very small power range, all the engines used are commercially available diesel engines, and there is a desire to eliminate the few gasoline engine sets altogether. The commercial diesel engine typically meets the performance requirements of Mobile Electric Power without significant penalty and has the advantage of the low acquisition and support costs associated with a large industrial base.

Table ES-3 shows the typical characteristics of some of the engines used in the DoD Standard Family of General Purpose Generator Sets. The engines must be of sufficient power that the electrical output from the set is maintained to a specified altitude and temperature. Stirling engine characteristics are shown also, based on scaling the size of the MTI Mod II engines to the appropriate horsepower levels. It appears that the scaled Mod II values are approximately the same as current diesels. To complete an engine installation, it is necessary to provide a radiator and coolant, which for the diesel typically adds one

Table ES-2. General Purpose Generator Sets in the US DoD Inventory

SIZE (kw)	AF ASSETS	NAVY ASSETS	MC ASSETS	ARMY ASSETS	TOTAL ASSETS
0.5	6	0	0	3,268	3,274
1.5	746	0	0	38,887	39,633
3	2,168	0	2,163	31,745	36,076
5	934	109	0	26,496	27,539
10	1,267	98	1,424	19,404	22,193
15	397	934	0	3,655	4,296
30	1,583	275	1,563	4,412	7,833
60	6,173	318	620	5,455	12,566
100	720	126	137	1,131	2,114
200	737	350	189	124	1,400
500	10	0	0	21	31
750	0	0	0	21	21
TOTALS	**14,741**	**1,520**	**6,096**	**134,619**	**156,976**

Source: NATO Exercise on Tactical Electric Power.

Table ES-3. Comparison of Typical Diesel Engines Used in DoD Standard Family Generator Sets and Stirling Engines

GENERATOR SET SIZE		DIESEL ENGINES	STIRLING ENGINES
			WEIGHT (LBS)
SIZE KW ELECTRICAL	BARE ENGINE HORSEPOWER	WEIGHT (LBS)	MOD II SCALED
30	60	610	492
60	120	970	984
100	200	1,400	1,640
200	400	2,800	3,280

pound per horsepower, and approximately 8 percent gross engine power to drive the cooling fan. These installation penalties are more significant for the Stirling engine since twice as much heat must be rejected through the radiator. Therefore, an installation weight penalty of approximately 2 lbs per horsepower must be assessed, and the cooling fan will require approximately 16 percent gross engine power. These installation penalties are included in the table. Thus, with installation penalties, the best current experimental Stirling is heavier than current, commercially available diesels. Furthermore, the Mod II is designed for a 3,500-hour light-duty, automotive lifetime; if it were scaled back to maximum pressures and piston speeds typical of long-life, heavy-duty diesels, then the weight per horsepower would be roughly doubled.

A low noise signature can be important to avoid detection. The Army's Survivable Tactical Army Generator (STAG) program requires a noise level less than 70 dBA at 7 meters. The diesel engine can meet this requirement only by being installed in a sound-insulated box, but this solution is acceptable from a weight, volume, and cost standpoint. One of the cited advantages of the Stirling engine is a lower noise level than the diesel. For the MTI Mod II Stirling engine, noise levels are reported to be 90 dB at mid power and speed and over 100 dB at full power. These values are indeed 10-20 dB less than the diesel engine (Deere reports that the Mod I is, on average, 6 dB quieter than their 3.6 l diesel); however, they are still sufficiently high that additional silencing would be required to meet the STAG requirement. The most cost effective method of meeting the signature requirements is to provide a suitable housing for the standard diesel set.

Another potential advantage of Stirling engines is the ability to function on a wide variety of fuels; however, this advantage is of limited usefulness in general purpose applications where a standard fuel supply is available and the fuel tolerance of available diesels is already adequate.

In conclusion, to the question "If Stirling engines were commercially available would they be used in general purpose generator sets by DoD?" the answer is yes, provided they were competitive with diesels in cost. The prospects for this to happen, however, seem remote since the need for additional heat exchangers makes the cost of any closed-cycle engines, even in large-scale production, more than the cost of equivalent open-cycle piston engines.

To the other question "Are general purpose generator sets a DoD application that warrants developing Stirling engines?" the answer is no, since there are no apparent major advantages that would justify such an investment; indeed, DoD does not now develop conventional diesel generator sets.

2. Special Purpose Sets

In addition to the battlefield power requirements which can be satisfied without undue penalty with the Standard Family of Generator Sets, there are sometimes systems which have extreme weight and volume constraints that cannot be satisfied by the Standard Family. In these cases, special generator sets may be warranted in order to obtain low weight and size. This is the case in the Patriot Missile System in which a turbine generator set is used. Turbine generator sets are very much smaller and lighter than diesel sets, but

have the disadvantage of higher fuel consumption and cost, making them inappropriate choices for general purpose sets.

The Free Piston Stirling Engine is a variation of the Stirling cycle which has unique characteristics which may be of military interest for special applications where low noise and multifuel capability are desired. The version of particular interest is the hermetically sealed engine with linear alternators directly connected to the free pistons. This design eliminates leakage of the hydrogen working fluid, and the engine could, in theory, be about as light and efficient as other small engine generator sets, and offer low noise and vibration. While this concept appears interesting, the experience with real engines to date has not been altogether satisfactory. Perhaps due to the inability to precisely control the location of the work and displacer pistons, the free piston engine does not have as high efficiency as the kinematic Stirling; further, the linear alternators have not operated at high efficiency. The Army Belvoir R&D Center has supported demonstration programs with MTI and Sunpower in the 3 kw category. The MTI program was terminated when authorized funds were expended and the engine was far from reaching performance goals. At the completion of the program with Sunpower, the power, fuel consumption, and reliability performance was also below goals.

In conclusion, the answer to the question "If Stirling engines were commercially available, would DoD use them for special purpose generator sets?" is yes, provided they could meet the special purpose requirements. Unfortunately, current demands for special purpose sets are to meet extreme size and weight constraints which the Stirling could not meet in competition with the gas turbine engine.

To the other question "Are special purpose generator sets a DoD application that warrants developing Stirling engines?" the answer is no. DoD does not develop new engines for use in generator sets, but instead adapts an available engine to this use. So far, efforts to adapt Stirling engines to this use have not been successful.

D. REMOTELY PILOTED UNDERWATER VEHICLES

The military need for small submarines ranges from tethered unmanned submersibles for underwater inspection to free-swimming vehicles that can carry a few people at a few knots for many hours. At least some of the applications are for surveillance and other missions that require very quiet operation. Open-cycle engines like the diesel suffer from such serious disadvantages in underwater applications that the competition is

not between open- and closed-cycle heat engines but between batteries and closed-cycle engines.

A high-density, energy source system becomes increasingly beneficial as the maximum design range or design speed of a vehicle increases. However, remotely piloted submarines' range will probably be limited by other considerations, most likely communication. If the range is limited to less than 100 miles, then lead-acid batteries are able to meet most mission propulsion requirements. For example, a hypothetical submersible 2 meters in diameter and 10 meters long operating at 10 knots for 10 hours requires 200 kw-hrs of stored energy. As shown in Table ES-4, lead-acid batteries provide about 35 W-hrs/kg, so less than 6 metric tons of batteries are adequate. This battery load makes up less than 18 percent of the weight of the nominal 100-mile range submersible and less than 8 percent of its volume. More advanced batteries (for example, silver/zinc or lithium thionyl chloride batteries) could reduce the battery weight load to less than 4 percent of the total vehicle weight at a penalty in cost.

Table ES-4. Underwater Energy Storage

	SYSTEM			
	LEAD/ACID STORAGE BATTERY	LITHIUM THIONYL CHLORIDE BATTERY	LI/SF 6 THERMAL REACTION	
			30% THERMAL EFFICIENCY	40% THERMAL EFFICIENCY
W - hrs/kg	35	540	939[a]	1,254[a]
W - hrs/l	80	1,000	698[b]	932[b]
Wt of 200 kW-hrs storage (kg)	5,714	370	213	159

[a] Assumes that 75 percent of the energy storage system mass is reactant and 25 percent is hardware.
[b] Assumes that 50 percent of the total volume of reactant and heat extraction system contains reactant. SF_6 at liquified densities.

A closed-cycle heat engine using heat from a constant-volume exothermic reaction has potentially better overall energy density than available battery systems. For example, the Stirling Power System's 15 kw, 100 kg V160 is very close to the size required to power the suggested nominal submarine. Heat could be provided by a reaction, like SF_6 on lithium, which produces about 4 kw-hrs of thermal energy per kilogram of reactant. Although the weight of the reactant storage and handling system must be added, of course, and the V160 can convert only 28 percent of that to mechanical work, the total propulsion package with a Stirling could be lighter than the propulsion package with advanced but available batteries. However, the remotely piloted submersible is limited, for reasons of

communication, to such short ranges that the propulsion system requirements simply are not very demanding and do not warrant sacrificing the reliability and mechanical and logistical simplicity of batteries.

A submersible may require energy for other mission requirements in addition to propulsion. Lacking a clear mission definition, specifying these requirements is difficult but, as an example, a slowly moving deep water searcher may require minimal propulsion energy but substantial energy for floodlights. At very short ranges, this energy could be provided by the umbilical connection. At longer ranges, an onboard power source is required. For these cases, endurance is like range in that shorter endurance missions will be best met by batteries and longer endurance missions may require some dynamic power source.

The Swedish government is experimenting with a remotely piloted small submersible powered by an SPS V160 Stirling engine. It is reported that this vehicle will initially be operated with an umbilical connection to another ship but in the future will be free swimming. If successful, this experiment would demonstrate a capability for long range unmanned submersibles; however, the difficulty of communicating with such a device, when the umbilical connection is removed, may limit its usefulness.

In conclusion, to the question "If Stirling engines were commercially available, would DoD use them in remotely piloted underwater vehicles?" the answer is yes, provided there were long range or endurance requirements and provided they were competitive with closed Brayton or Rankine cycle systems.

To the other question "Are remotely piloted underwater vehicles a DoD application that warrants the development of Stirling engines?" the answer is that DoD would probably not develop a new engine for this purpose, most likely batteries would be the energy source. If a dynamic power source were required, DoD could adapt an existing engine as has been done in the Swedish experimental vehicle that is using the SPS-V160 engine. The competition would be with other closed-cycle engines. If new missions arose that placed more severe demands on the propulsion systems for remotely piloted underwater vehicles, then this issue would be reevaluated.

E. NON-COMBAT VEHICLES

Non-combat vehicles of a wide variety are used in the Department of Defense. They are typically on-highway and off-highway trucks from one-quarter to 10 or more tons

of payload capability, ambulances, fire trucks, fork lifts, construction equipment, etc. In virtually all cases, the system and mission has a commercial counterpart, so that commercial items are used as available off the shelf or with some minor modifications. Some families of military engines have been developed to try to achieve the benefits of standardization in tactical vehicles; however, the general result has been that overall program economies were best achieved with off-the-shelf commercial engines which were well developed for commercial use, were available at low cost, and could be supported with widely available spare parts. Engines for non-combat vehicles are typically in the 100 to 500 horsepower range and are essentially the same as those used in generator sets, described above.

Since the early 1970s, the Department of Energy has spent over $100 million on development of an automotive Stirling engine. Over 2,000 hours have been logged in test vehicles. The US Air Force has participated in the field tests using first a Mod I engine in a van, which was operated approximately 6,000 miles, and then a Dodge D-150 pickup truck with a Mod I+ engine, which contains some improvements and has now been operated nearly 10,000 miles. Operation included flight line service at Eglin AFB, highway driving to Randolph AFB, Texas, taxi service at Randolph AFB, and highway driving to Washington, DC, for demonstration purposes. Fuels used include JP-4 jet fuel, diesel fuel, and gasoline, with satisfactory operation on each. The power rating of the Mod I+ engine in the pickup truck is 75 hp, only about one-half that of most common full-size pickup trucks. The performance is therefore deficient compared to typical pickup trucks, although it has operated satisfactorily at speeds of 60 mph on the highway. The pickup truck has achieved about 22 mpg on the highway at average speeds of 50 mph. This is some improvement over the spark ignition engine previously installed. Part of the improvement is due to lower installed power, part is due to the higher energy content of diesel fuel than gasoline, and part may be due to intrinsic higher efficiency of the Stirling over the spark ignition engine. It is difficult to separate out these effects and a fair comparison would be between the 75 hp Stirling and a 75 hp diesel.

No fundamental problems were encountered which would raise questions as to the soundness of the Stirling engine concept; however, as would be expected from an undeveloped engine and installation, many small problems arose and maintenance actions were taken. Examples of problems are O rings, seals, vent filters, oil pump, ignitor wire shorts, control valves, and hydrogen leakage. The most significant of these problems would appear to be the requirement to replenish the hydrogen working fluid which leaks

from the system. This has been improved from an initial replenishment daily to replenishment every six days. Long term sealing of hydrogen remains a significant development problem. Further vehicle experience will be gained, starting in the summer of 1988, when a Postal Service van will begin operation using a further improved Mod II engine.

In conclusion, the answer to the question "If Stirling engines were commercially available would DoD use them in non-combat vehicles?" is yes, provided they were competitive with open-cycle engines in cost. As noted above in the discussion of general purpose generator sets, the prospects for this happening are remote.

To the other question, "Are non-combat vehicles a DoD application that would warrant developing Stirling engines?" the answer is no. DoD no longer develops special engines for non-combat vehicles but instead uses commercially available engines.

F. COMBAT VEHICLES

Combat vehicles are typically armored, tracked vehicles which have power requirements in the 300-1,500 hp range. The duty cycle is approximately 40 percent operating time at idle, 40 percent time at low to medium power, and up to 20 percent time at high power. Since the entire propulsion package (engine, transmission, accessories, fuel tanks, etc.) is surrounded by heavy armor, it is important that the total propulsion package volume be minimized. This dictates engines which have high specific output to minimize engine volume, and also have low fuel consumption, particularly in the lower power range, to minimize fuel volume. Unlike the case of the Standard DoD Family of Generator Sets and the non-combat vehicle, off-the-shelf diesel engines are not suited to the combat vehicle application, since the commercial diesels are conservatively designed for long life and are, as a result, too large and heavy. Gasoline engines are smaller than diesel engines, but have higher fuel consumption which offsets the engine volume advantage. Also, gasoline is undesirable in a combat vehicle due to the fire hazard.

In smaller sizes, commercial diesel engines are often uprated as much as 50 percent and used in combat vehicles, accepting the compromise of shorter life in order to gain the smaller volume. In the main battle tank size (vehicles of approximately 60-tons and 1,500 hp), no commercial diesels are available which are suitable or which can be uprated satisfactorily, and therefore special engines must be developed. Special compact, high output diesels developed for this application may have pound-to-horsepower ratios of

approximately 3, and the M1 battle tank uses a specially developed recuperative gas turbine which has a ratio less than 2 lbs/hp.

The volumes of the various components of a main battle tank propulsion package installation are shown for various engines in Table ES-5. The "existing diesel" characteristics are an average of the similar MTU-883 and the CV-12R. The "advanced" engine characteristics come from the Turbine (or Diesel) Advanced Integrated Propulsion System designs. The Stirling engine performance characteristics are extrapolated from the Mod II automotive engine with some allowance for improvement in power volume density. The Stirling engine not only has a high basic volume, but it also suffers installation penalties due to the cooling system requirements. As noted above in the discussion of generator sets, a Stirling engine must reject all its waste heat through radiators, which results in radiators approximately twice the size and weight of a diesel engine, and the cooling fan power is also doubled relative to the diesel. At least 10 percent of the gross engine power is required to drive the cooling fan for the buried installation of the diesel engine in a combat vehicle, and at least 20 percent would be required for the Stirling engine installation, resulting in even higher basic Stirling engine power requirements to meet the same vehicle performance.

The Mod II Stirling engines used to scale to the values shown in the table operate at 3,000 psi peak cylinder pressure. While experimental diesel engines have been operated to 3,000 psi, none are in production, and the typical long life diesel does not exceed 2,000 psi. Also, the Stirling engine is rated at 4,000 rpm, whereas the diesel engines are less than 3,000 rpm. These factors indicate that the Stirling engine characteristics already are typical of a short life engine and do not leave much room for uprating.

The wide range of fuels which can be used in the Stirling engine is desirable, but advanced diesels already have broad fuel tolerance. The fuel consumption is like the diesel, lowest at mid to low power levels and is therefore well matched to combat vehicle requirements, but these advantages are far offset by the large volume requirement of the installed engine. While the volume of the Stirling engine might be reduced through advanced technologies which permit operation at even higher temperatures and mean cycle pressures, the gains are not expected to be sufficient to offset the large current disadvantage. In addition, the same technologies which permit higher cycle pressures in the Stirling would also permit higher peak pressures in the diesel engine, with correspondingly higher output.

ES-11

Table ES-5. Volume Relationships for Combat Vehicle Power Packs

COMPONENT	EXISTING DIESEL POWER PACKS FOR TANKS. NOMINAL RELATIVE COMPONENT VOLUMES (percent)	ADVANCED DIESEL COMPONENT VOLUMES RELATIVE TO TOTAL DIESEL VOLUMES (percent)	ADVANCED TURBINE COMPONENT VOLUME RELATIVE TO TOTAL DIESEL VOLUME (percent)	STIRLING ENGINE COMPONENT VOLUME RELATIVE TO TOTAL DIESEL VOLUME (percent)
Transmission	21	20	17	21
Cooling	19	9	3	42
Engine	29	27	15	96
Fuel	25	22	29	27
Air Cleaner	5	4	8	2
Exhaust	1	1	6	1
Total	100	83	76	189

In conclusion, the answer to the first question "If Stirling engines were available commercially, would DoD use them for combat vehicles?" is no since there are no prospects that any closed-cycle engine could meet combat vehicle volume constraints. For this same reason, DoD would not undertake development of Stirling engines for combat vehicles; so the answer to the second question is also no.

G. AUXILIARY POWER UNITS

Auxiliary power units (APUs) are usually small engines (under 100 horsepower) which provide auxiliary power in the form of electricity, pneumatic energy, or hydraulic energy to the system in which it is installed. Applications include starting power for aircraft, standby or emergency electrical power, or other uses in systems where power is not provided by the primary propulsion system. In aircraft, it is important that APUs be of light weight, and in combat vehicles it is important that the installed volume be small. In both cases, simple cycle gas turbines are typical choices. The Stirling cycle APU is neither low weight nor low volume and is therefore not usually competitive with the turbine in these applications.

Future combat vehicles are projected to have increased requirements for onboard auxiliary power, and the Stirling engine, particularly the Free Piston Stirling Engine, may have practical advantages for a silent watch mission where low noise, vibration, and emissions may be important, if the installed volume can be reduced to an acceptable level. The free piston Stirling engine has not yet had the benefit of significant development funding, therefore the characteristics of practical engines are not fully established, although, as noted above, the results to date have been disappointing. Table ES-6 shows the characteristics of a current free piston Stirling engine and a commercial diesel engine power unit of equivalent size, which could be used as an APU. Both systems would appear to be too large and heavy for battle tank application since the power requirements can be 5-10 times higher than those of the units shown, and a turbine engine power unit would be preferred.

In conclusion, the answer to the first question "If Stirling engines were commercially available, would DoD use them for auxiliary power units?" is yes, on a competitive basis. It appears, however, that the Stirling would have difficulty competing with the turbine, if size and weight are important, or with the diesel, if cost were important.

Table ES-6. Typical Small Power Units

	WEIGHT	VOLUME	EFFICIENCY
3 kw Free Piston Stirling Engine Unit	300 lbs	12 cu. ft.	25%
3 kw Diesel Engine Unit	348 lbs	8.5 cu. ft.	30%
50-100 HP Multipurpose Small Power Unit – Turbine Engine and Gearbox	120 lbs	1.5 cu. ft.	18%

The answer to the other question, "Are auxiliary power units a DoD application that warrants developing Stirling engines?" is no. In general, DoD does not develop new engines for auxiliary power units but adapts existing engines to this use.

H. SPACE POWER

For space application, low power consumption is met by photovoltaic arrays. Intermediate levels of power are met by thermoelectric generators powered by radioactive decay. For the largest power needs, some sort of dynamic power generation system is required, either nuclear or solar powered. As with underwater application, open-cycle engines are not able to compete with closed-cycle engines in space. The competition for dynamic systems, then, is among various closed-cycle engines, the foremost being the Stirling and the closed Brayton.

The efficiency of a space-based power system is critical to the overall weight which is, of course, of primary concern for space operations. High efficiency decreases system weight in two ways. For any given output power, the more efficient the conversion system is, the smaller the heat source can be. and at the same time higher efficiency results in less waste heat to be rejected, which reduces the size of the required radiator. Reliability is the other high priority for any space application. Typically, this translates into simplicity of design, few moving parts, some redundancy, and a system that does not fail catastrophically. Areas of special concern for reliability considerations are sliding seals, bearings, and vibration.

The kinematic Stirling has potentially high efficiency, but the reliability of the system of connecting rods and crankshafts is not high enough for space application. The only Stirling design seriously considered for space application is the Free Piston Stirling engine. However, because of lack of precise volume control with free pistons, the cycle efficiency of the free piston engine may be lower than a kinematic Stirling. On the other hand, the free piston engine does not suffer from mechanical losses in the crankshaft. This

may compensate somewhat for cycle losses, and the efficiency of the two, at least at the optimal design point, are potentially very close. High linear alternator efficiency has not yet been demonstrated but there is no fundamental reason that it should be unobtainable. The main competitor for dynamic power is the closed-cycle turbine engine, either using a Brayton or Rankine cycle. Closed Brayton systems can operate in enclosed working gas environments which eliminate leakage, can use gas bearings which essentially eliminate wear, and can operate at reduced pressure which maintains good efficiency at part power. The turbine engine potentially has a single moving part containing the compressor, turbine, shaft, and alternator armature. The Stirling engine has two moving pistons per cylinder and at least two cylinders. The turbine has potentially very low vibration and the Stirling engine, with an arrangement of opposed cylinders, can balance the motion of the reciprocating pistons to achieve low vibration levels.

The closed-cycle turbine engine and the Stirling engine thus appear to be potential competitors for the space power mission. The advantages of the Brayton are light weight and high demonstrated efficiency in large sizes. The Stirling--like any other reciprocating engine--can never be as light as a turbine engine, it can compete only by achieving greater efficiency. Turbomachinery has poor efficiency in very small sizes where positive displacement engines operate well (NASA's Stirling version of the SP-100 would be made up of coupled 25 kW generators, quite small for turbine engines). Since turbomachinery increases in efficiency in larger sizes, the Stirling will be better able to compete at the lower end of the dynamic power generation range. A possible hierarchy of power sources, from small to large, could be: photovoltaic, thermoelectric, positive displacement (e.g., Stirling), and turbine.

In conclusion, the answer to the question "If Stirling engines were commercially available, would DoD use them for space power applications?" is yes, but it is extremely unlikely that any commercial engine would meet the specialized requirements of a spacecraft power source.

To the other question, "Is space power a DoD application that would warrant developing Stirling engines?" the answer is that DoD might engage in some development activity provided the Stirling engine could demonstrate its potential for high efficiency together with the long life, high reliability, and zero maintenance needed for space operations. If the NASA exploratory program with the free piston Stirling is successful, the issue could be evaluated by DoD competitively with other closed-cycle systems.

I. SUMMARY

In the applications considered here, the major advantages cited for the Stirling engine are multifuel capability, efficiency, and low noise levels. These potential advantages are small compared to current diesels. Diesels are already able to burn broad-cut fuels, have high efficiency, and can be adequately muffled. Their major disadvantages are size, weight, and cost. These disadvantages are only severe in vehicular and mobile power applications where the competition is open-cycle internal combustion engines (diesel, spark-ignition, or turbine). In underwater and space power applications where closed-cycle engines are a necessity, the use of Stirling engines shows more promise.

All closed-cycle engines, when compared to open-cycle internal combustion engines, suffer from weight, volume, and cost disadvantages. The steam engine lost out to the internal combustion engine in the automobile market for these reasons in the 1920s and again when a revival was attempted in the 1970s. In addition, today, because of the huge annual production of internal combustion engines, their cost is relatively low and their reliability well developed. Moreover, even if a closed-cycle engine were in high production, it would be more expensive than an open-cycle engine because of its need for additional heat exchangers.

For non-combat vehicles, generator sets and auxiliary power units, cost is a major consideration and the military has opted to use commercial internal combustion engines (mostly diesels). For such general purpose use the weight, size, and cost disadvantages of any closed-cycle system far outweigh the possible advantages; in fact, commercial open-cycle engines have won out over specially developed open-cycle engines in these applications because of lower cost.

For some military uses, however, commercial engines will not meet the requirements and special engine developments will be undertaken, for example, armored combat vehicles where the volume constraints are so severe that special engines are required and their development is paid for by the military. Unfortunately the severe volume constraint eliminates consideration of any closed-cycle engine for this application.

Mobile power units also have special requirements, generally severe size and weight constraints, that require special power units. These demands have been met by using gas turbine engines at a penalty in increased cost. Again, closed-cycle systems could not compete here because of their inherent size and weight disadvantage.

Two applications considered here, underwater vehicles and space power, require the use of closed-cycle systems, thus eliminating open-cycle systems from the competition. In these areas, the Stirling engine competes with other closed-cycle systems, generally turbomachinery using Rankine or Brayton cycles. The advanced state of development of turbomachinery makes this a tough competition for Stirling engines. However, in Sweden an experimental small submersible is being powered by a Stirling engine; and in the United States NASA is experimenting with Stirling engines for space power applications. Whether this will lead to wider practical use of the Stirling engine in these application areas is not clear; but so far the Stirling has not demonstrated clear-cut advantages over other closed-cycle systems.

EVALUATION OF POTENTIAL MILITARY APPLICATIONS OF STIRLING ENGINES

A Stirling engine is a heat engine that operates on a closed thermodynamic regenerative cycle in which the flow of working fluid is controlled by volume changes. The working fluid experiences periodic compression at low temperatures and expansion at high temperatures, so there is a net conversion of heat to work. The thermodynamic cycle consists ideally of two isothermal and two constant volume processes, and is similar to the Carnot cycle, which has the highest efficiency of heat engine cycles. It is this potential for high efficiency which is of major interest for many engine applications. In addition, the Stirling engine has an external, steady flow combustor which permits the use of a wide range of fuels, can be low noise, and permits low emission of pollutants in the exhaust.

The cycle, performance, physical arrangements, and other characteristics of the Stirling engine are described in considerable detail by Graham Walker in Appendix A.

A. POTENTIAL ADVANTAGES OF THE STIRLING ENGINE

The Stirling engine has many claimed advantages, all of which have been demonstrated in some engine even though no one engine has demonstrated all of them. These advantages include:

> High efficiency
>
> Clean burning and low emissions
>
> Multiple fuel capability
>
> Low noise and vibration
>
> Reliability.

Each of these advantages is discussed in some more detail below.

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1. High Efficiency

A theoretical Stirling engine is often described as a Carnot engine, which has the highest thermodynamic efficiency theoretically possible. However, because of mechanical limitations, for example, continuous piston motion, even the theoretical efficiency of a real Stirling engine will be lower. In addition, losses due to friction, heat exchanger efficiency, etc., will reduce further the achievable efficiency of a real Stirling engine.

Even with the unavoidable limitations on the cycle and inevitable inefficiencies of a real engine, the Stirling engine should be able to attain a somewhat higher efficiency than a *simple* diesel. In some engines, this high efficiency has already been demonstrated. However, diesel efficiency is continuing to improve and the demonstrated efficiency of low heat rejection turbocompound diesels are just as high as what can be hoped for in the Stirling engine but which has not yet been demonstrated.

Although the Stirling engine is usually advanced for its high efficiency, any particular application often requires compromises of efficiency for other mission goals. For example, to improve power-to-weight ratios, the engine speed can be increased but this increases aerodynamic and thermal inefficiencies in the recuperator which reduces overall efficiency. It is important therefore to compare the Stirling engine to competitive engines that have been developed for the same target application. It is incorrect, for example, to compare the efficiency of a stationary power Stirling engine to an automotive diesel or to compare the horsepower per pound of an automotive Stirling engine to a stationary diesel.

The Stirling engine efficiency is high but the competitive diesel could also improve in efficiency if an incentive existed. The demonstrated efficiency of the diesel is there; putting it in the field is dependent on market incentives. When fuel prices increased, internal combustion (IC) engine efficiency was increased quickly. The fact that even more efficient IC engines are possible but are not being marketed should be a caution sign for the Stirling engine.

2. Clean Burning and Low Emissions

Because the Stirling engine is an external combustion engine, the fuel can be burned in an easily controlled, steady state, oxygen-rich flame in a hot combustor which leads to low pollutant emissions. This is characteristic of all external combustion engines. Spark ignition engines can reduce pollutants with external catalytic converters and a fair comparison in this case should include the weight and cost of the converter. The military

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primarily uses diesel engines. Diesel particulate emissions foul converters so quickly as to make converters impractical. It is more difficult to agree on the basis of comparison in this case. The military must meet civilian pollution standards for tactical vehicles but is exempt from controls on combat vehicles. Meeting civilian standards for tactical vehicles is not much of an additional imposition since tactical vehicles invariably use civilian engines.

3. Low Infrared Emissions

Much is made of the low infrared emissions possible with the Stirling engine. Low infrared emission is an advantage for tactical power systems because it makes the generator more difficult for the enemy to find or home on with infrared sensors. There are two aspects to this characteristic advantage of the engine, one real and the other largely artificial. The real advantage comes from the high efficiency of the engine. Efficiency is, by definition, just the useful work out divided by the total energy in. The difference between the energy in and the work out is the waste heat. For any given workload, it is easy to see that the higher the efficiency, the less waste heat rejected. A 100 percent efficient--and thermodynamically impossible--engine would produce no waste heat at all. High efficiency of an engine results in lower total waste heat rejected to the environment. If the Stirling engine had a specific fuel consumption 10 percent less than a competitive engine, it would reject about 10 percent less heat. As noted in Section A.1, however, the Stirling engine does not have any potential efficiency advantages compared to high-efficiency diesels.

The claims of low infrared emissions due to low exhaust temperature are a largely artificial advantage. The very low exhaust temperature sometimes quoted for the Stirling engine obtain only after mixing the combustor flue gases with the radiator cooling air. Open-cycle engines reject a great deal--often most--of their waste heat in the exhaust gas. The Stirling engine is a true heat engine and rejects all of its thermodynamic waste heat into the cold temperature heat sink. This effect alone roughly doubles the radiator loading compared to a diesel and hence the radiator air flow is higher. Moreover, the heat will often be rejected at a lower temperature relative to a diesel radiator which further increases the necessary radiator air flow. (This results because the cooling of an internal combustion engine is to keep the metal temperatures within acceptable bounds, which means that the designer is trying to "cool" at the highest possible temperature he can get away with. On the other hand, the cooling for the Stirling engine is to provide a thermodynamic heat sink and the designer is trying to cool at the lowest possible temperature to increase efficiency.) With the very large air flow of the Stirling engine it should hardly be surprising that the

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overall exhaust temperature of the combined radiator air and flue gas is low. On the other hand, there is nothing that prevents mixing the exhaust gases of a conventional internal combustion engine with the radiator air to reduce the temperature of the exhaust. One could even install an oversized fan on a diesel to provide additional mixing air. For a fixed level of heat rejection, the temperature rise will be inversely proportional to the air flow available to cool the exhaust gases; the low temperature of the Stirling engine exhaust is nothing more profound than that.

The low chemical emissions from the Stirling engine may provide some benefit toward reducing infrared emissions. The emission of the exhaust is a function of the temperature and the radiative characteristics of the exhaust. It is possible that the exhaust of the Stirling engine is less emissive than that of an internal combustion engine; for example, carbon dioxide is a poorer infrared emitter than carbon monoxide. Stirling engine emissions are also lower in particulates and nitrous oxides. Stirling engine and internal combustion exhausts would have roughly the same amount of water. This effect is complex and outside the scope of this report but measurements could easily be made to test it.

4. Multiple Fuel Capability

Although the multiple fuel capability of the Stirling engine is invariably listed as an advantage, particularly for military applications, part of this advantage is out of date, part is unobtainable, part is not unique to the Stirling engine, and part is real.

In the past, the Army worked simultaneously toward two separate goals that might have appeared somewhat contradictory. One was broad fuel tolerance, being able ideally to burn anything from crude oil to alcohol. The other was to have all military engines run off of a common fuel, specifically a light diesel. After much research, the Army seems to have decided that there is a compromise that achieves the advantages of both approaches: have all vehicles use a common *broad-cut* fuel. Once the Army has tanks, trucks, and helicopters running off the same fuel, adding a generator set that can use that fuel or gasoline is of very limited advantage since the generator will inevitably run always on the standard Army fuel. This part of the purported advantage is out of date since multifuel capability is no longer an important Army R&D goal. Broadening the fuel tolerance slightly more still has advantages (but that is possible with diesels).

For civilian and military applications the advantage of the multifuel capability will be largely unobtainable because the Stirling engine will exist in a greater fuel economy that

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will be dominated by internal combustion engines for the foreseeable future. Therefore, the refining and distribution system will be geared to providing basically what it provides today, gasoline and light diesel with very minor variation (for example, a couple of gasoline octanes and summer and winter diesel). Even if the Stirling engine can burn wood chips, typically it will never have the opportunity because there is no wood chip distribution network. Moreover, other continuous combustion engines, for example, Brayton cycle turbines, have multifuel capability but in order to achieve near perfect combustor efficiency, the fuel injectors and combustors are designed for a particular fuel. A turbine engine can burn gasoline but to do so efficiently requires a different combustor design.

A fuel economy with some Stirling engines but still dominated by internal combustion engines will probably be restricted to gasolines and light diesel. The *ability* to burn alternate fuels does not mean an *advantage* to burning alternate fuels can necessarily be realized. A counter-argument to this point arises if the Stirling engine became an intermediate step in a long-term plan to switch from one fuel economy to another, from gasoline to alcohol, for example. In this case, a multifuel engine could be introduced to provide a market for alcohol but still burn gasoline when or where alcohol is unavailable. When the multifuel engine used 10 to 20 percent of the fuel *and* there was an advantage to using alcohol, one would expect alcohol to be widely available. At that point, alcohol-only engines could be phased in and gasoline engines phased out. However, this is not a goal that would warrant DoD support for a new engine development.

Part of the advantage of multifuel capability obtains because the Stirling engine is an external combustion engine or a true heat engine, requiring only a heat source and heat sink to produce power. As such, the same advantage applies to all heat engines, for example, closed Brayton cycle engines or Rankine cycle engines. Indeed, the multifuel capability of a steam engine is identical to that of a Stirling engine and the utility of multifuel capability should be the same. An interesting inquiry would be to investigate whether Rankine cycle operators feel their multifuel versatility is important and how much use they make of it. Similarly, as pointed out above, turbine engines in principle could burn kerosene or gasoline but no deployed turbine makes use of that capability.

This is not to say that fuel versatility--or more accurately heat source indifference-- is unimportant, indeed, for underwater applications it is critical, just that the Stirling engine is not alone in enjoying the advantage.

5. Low Noise and Vibration

Much of the noise of internal combustion engines is due to unsteady combustion. High speed turbomachinery produces characteristic noise that can be reduced but not eliminated. The external combustion Stirling engine does not suffer from these inherent noises and is potentially quieter than its competitors. Competitive engines can always be made quieter but at some cost. For example, internal combustion engines can be muffled and surrounded with sound absorbing boxes. This quieting will reduce power or efficiency, or increase volume and weight, or otherwise penalize the competitive engine. On the other hand, some noise comes from accessory devices, for example, fans, fuel and water pumps, alternators, etc., that the Stirling engine will have in common with competitive engines. Comparisons should be made first between Stirling engine and quieted competitive engines and, second, between all-up Stirling engines with accessories and all-up competitive engines with accessories.

6. Reliability

Many of the characteristics of the Stirling engine should result in inherent high reliability. Moving parts are never exposed to the highest temperature of the combustor. High temperature parts are not subject to rapidly fluctuating temperature, except during startup. Lubricating oil is never exposed to combustion products The engine has potentially few moving parts. In spite of this, to date most Stirling engines have demonstrated significant reliability problems. In part this is to be expected of any new engine because reliability is typically increased by running engines, finding where they fail, fixing the fault, and running them some more. In short, developing really high reliability requires experience that most Stirling engines do not have.

One inherent characteristic of the Stirling engine results in most of the reliability problems. The engine operates on a closed cycle, typically uses hydrogen or helium as a working fluid, and--in order to achieve high power to volume--operates at high pressure. Whereas an open-cycle engine gets a new charge of working fluid with each cycle and can afford losing working fluid to the environment, the Stirling engine cannot and the seals between the working fluid and the environment become critical. Because the working fluid is high pressure hydrogen, the seal problem is particularly challenging.

Free piston Stirling engines solve this seal problem in one of two ways. Neither type of free piston Stirling engine transmits power out through connecting rods. One type transmits power to a hydraulic fluid that in turn transmits power out to some mechanical

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device. These can be thought of as just kinematic Stirling engines with two-stage seals; one stage is a gas-liquid seal with no net pressure difference which is relatively easy, and the other stage is a high pressure oil-air seal which is relatively easy. In other words, one stage keeps in the hydrogen and the other stage keeps in the pressure. The other type of free piston engine can be completely enclosed with no moving seals at all. This type uses a magnetized power piston to transmit power out through the pressure walls in the form of moving magnetic fields. Conducting coils outside the pressure walls convert the oscillating magnetic fields into electric power. If electric power is what is desired, then this is a very attractive solution. If mechanical power is required, then an additional step is involved of converting through an electric motor, reducing significantly the overall attractiveness of the scheme.

Seals are not the only potential reliability problem. To get acceptable power densities, the Stirling engine must operate at high pressures. Some designs expect pressures and temperatures that have not yet been demonstrated in diesel engines and are beyond the current capabilities of long-life systems. These high pressures require new material technologies or reliability will suffer.

B. CONSIDERATIONS OF SYSTEM, MISSION, AND APPLICATION

In any engine utilized in a system, the requirements of the system must be satisfied in some optimum way to satisfy the mission. For example, an aircraft engine must be light in weight with generally low fuel consumption to permit the aircraft to fly with some payload. A battle tank must have an engine with low volume and good fuel consumption at low power to minimize the propulsion volume which must be surrounded by armor. A truck need not have a particularly lightweight engine, but fuel consumption is important, as is the acquisition cost of the engine. Some applications, such as the aircraft and tank, have system and mission requirements which warrant the development of special engines. Most tactical vehicles, such as trucks and general purpose electric power generation, do not require specially developed engines and use commercially developed items quite satisfactorily, usually diesel engines.

In considering the military application of a Stirling engine, it is necessary to establish how the Stirling engine can satisfy requirements in a better way than other available engines. The engine which has broad characteristics most similar to the Stirling engine, and with which the Stirling would typically compete, is the diesel engine and some discussion of the relative merits of each engine will be presented. The Stirling engine

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compared will be the kinematic Stirling, providing shaft horsepower output. Both the Stirling and diesel engines are larger and heavier than gas turbine engines and automotive gasoline engines. Both offer better fuel consumption than these engines, and both offer the best fuel consumption in the mid- to low-power range. Furthermore, gasoline engines are undesirable in the combat theater because of the danger of gasoline fuel.

Approximately 8 million diesel engines are produced worldwide each year. Thus the diesel engine is well developed, is used worldwide in a wide variety of applications, and is produced at an acceptable cost for these applications. It is available over a very wide power range, from approximately 10 horsepower to over 50,000 horsepower for heavy industrial application. Most diesel engines are in the 10 to 2,000 hp range which corresponds to the range that is of interest to the military. Light duty automotive type diesel engines in the 100-200 hp category weigh on the order of 5-7 lbs/hp, while heavier duty engines for industrial and truck application weigh 8-10 lbs/hp. These heavy duty engines are designed for long life under high load conditions and lives of 5,000 hours or 300,000-500,000 miles before overhaul is required. The thermal efficiency of these engines is on the order of 35 to 40 percent uninstalled (the installation and cooling losses will reduce these efficiencies approximately 10 percent). The trend in recent years is for both specific weight and thermal efficiency to improve continually through the use of turbochargers, intercoolers, improved fuel injection equipment, etc. The "adiabatic" or insulated or low heat loss diesel engine with turbo-compounding (recovery of exhaust energy through a turbine geared to the crankshaft) which is now under development promises as much as 50 percent thermal efficiency. In addition, there are special purpose diesel engines which have been developed for special applications, such as combat vehicles, which have much higher output than commercial diesel engines, weighing only around 3 lbs/hp, at the expense of the long life expected in commercial applications.

Stirling cycle engines have not yet been developed to the point of production usage. The current state of the art of kinematic Stirling engines is shown in the Table 1. The most significant development funding has been provided to MTI, Inc., by the Department of Energy for automotive application. Well over $100 million have been expended on this project, and the resulting 80 hp (60 kw) engine is probably the most advanced Stirling engine at this time. It has demonstrated 40 percent thermal efficiency at a weight of approximately 6 lbs/hp. The development status of this engine can probably be considered analogous to an engine in the military development process which has completed the 6.3A Technology Demonstrator phase, and could now enter the 6.4 Engineering Development

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Table 1. US Kinematic Stirling Engine State of the Art

Firm	Model	Number Built	Operating Hours	Power (kW)	@RPM	Working Gas
MTI	Mod I	4	*	54	4,000	hydrogen
MTI	Mod I+	7	18,600	58	4,000	hydrogen
MTI	Mod II	2	800	60	4,000	hydrogen
STM	STM4-120	2	100	25	1,800	helium
SPS	V160	130	340,000	15	1,800	helium

* Included in Mod I+

Firm	Model	Number Pistons/ Volume per Piston (cc)	Hot Temp. (deg C)	Maximum Pressure (MPa)	Power Density (kG/kW)	Max. Thermal Efficiency	Mean Time Between Failures
MTI	Mod I	4/123	720	15	6.7	35%	15
MTI	Mod I+	4/125	820	15	6.1	37%	50
MTI	Mod II	4/120	820	15	3.7	40%	–
STM	STM4-120	4/120	812	13	6.7	45%	–
SPS	V160	1/160	720	15	6.7	28%	3,000

Note: All information is as provided by manufacturers.

phase with confidence of meeting the performance to a predictable schedule and cost. It must be kept in mind that the technology demonstrated is a "light duty" automotive design, and the long life under heavy load of the heavy duty diesel will not be realized. As the heater head temperatures and internal pressures are further increased for high efficiency, problems of component failure and containment of hydrogen will be further aggravated.

From the above, it is noted that for military applications that require the light weight and portability of the gas turbine engine, or the small volume of the special combat vehicle die el or turbine engine, the Stirling engine is not now a contender. For general purpose applications, such as mobile electric power generation or tactical vehicles, the Stirling engine could be considered as an alternate to the diesel engine. However, inasmuch as the diesel engines are already well developed and widely available at low cost, there is no apparent justification for the lengthy and costly development of a Stirling engine which has weight and efficiency characteristics competitive only for general purpose applications and is expected to be more costly than the diesel.

In order to warrant the high development and procurement cost of a Stirling engine, it is necessary that a special military application be identified which has an urgent need for the particular characteristics for which the Stirling engine has an advantage. These

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characteristics might be expected to be broad fuel tolerance and low noise level. So far, no requirement has been identified which is of sufficient importance to warrant the high costs of Stirling engine development, and requirements have been met satisfactorily with greater cost effectiveness with current or modified engines.

In general, the Stirling engine compares unfavorably with internal combustion (IC) engines. However, IC engines cannot operate in some environments, for example, underwater or in space, so closed-cycle engines are required. In these cases the competition to the Stirling are other closed-cycle engines and the Stirling looks relatively better.

The Free Piston Stirling Engine (FPSE) is a variation of the Stirling cycle which has unique characteristics which may be of military interest. The characteristics of current engines are shown in Table 2. The version of particular interest is the hermetically sealed engine with linear alternators directly connected to the free pistons. This concept eliminates the problem of leakage of the hydrogen working fluid, should be as light and efficient as

Table 2. Stirling Engine Characteristics Versus Military Applications

| Cited Potential Advantages: | ALREADY DEMON- STRATED? | Applications | | | | | |
		UNDER WATER	MEP	APU	COMBAT VEH.	OTHER VEH.	SPACE
Low Noise/Vibration	Yes	●	○	●	○		●
Low Thermal Emission	Yes		○	●	●		
Fuel Choice	Yes	●	○	○		○	●
High Efficiency	No	○	○		●	○	●
Low Maintenance	No	○	○	○	○	○	●
Disadvantages:							
Cooling Requirements					≡	≡	
Power/Weight Ratio				≡	≡	≡	≡

● Critical need

○ Advantage

≡ Important liability

other small engine generator sets, and offers very low noise and vibration levels. Due to the inability to precisely control the desired location of the work and displacer pistons, the FPSE may not have the potential for as high efficiency as the kinematic Stirling. There has not been significant development funding applied to the FPSE concept, so it is not as advanced in development as the kinematic Stirling. This engine would appear to offer the potential of satisfying the technical requirements for the Army's SLEEP ROC (Silent Lightweight Electric Energy Plants Required Operational Capability) although justifying the development costs is less clear.

1. Combat Vehicle Applications

Combat vehicles are typically armored, tracked vehicles which have power requirements in the 300-1,500 hp range. The duty cycle involves approximately 40 percent operating time at idle, 40 percent time at low to medium power, and up to 20 percent time at high power. Since the entire propulsion package (engine, transmission, accessories, fuel tanks, etc.) is surrounded by heavy armor, it is important that the total propulsion package volume be minimized. This dictates engines which have high specific output to minimize volume, and low fuel consumption, particularly in the lower power range, to minimize fuel volume for the mission. Off-the-shelf diesel engines are usually not suited to this application, since the commercial diesels are conservative, thereby large and heavy, and occupy too much volume. Gasoline engines are smaller than diesel engines, but have higher fuel consumption which offsets the engine volume advantage. Also, gasoline is undesirable in a combat vehicle due to the fire hazard.

In smaller sizes, commercial diesel engines are often uprated as much as 50 percent and used in combat vehicles, accepting the compromise of shorter life in order to gain the smaller volume. In the main battle tank size (approximately 60-ton vehicles and 1,500 hp), no commercial diesels are available which are suitable or which can be uprated satisfactorily, and therefore special engines must be developed. Special compact, high output diesels developed for this application may have power-to-weight ratios of approximately 3, and the M1 battle tank uses a specially developed recuperative gas turbine which is less than 2 lbs/hp. The recuperative cycle was chosen to reduce the fuel consumption at low power to better match mission requirements, and offer fuel consumption similar to a diesel, in spite of the fact that the heat exchangers result in engine volume being almost as much as the diesel.

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It can be seen from Table 1 that the sizes which have been demonstrated to date are considerably below the normal range of interest for combat vehicles and that the specific weights are above that of current combat vehicle engines. The specific volume of bare Stirling engines may be comparable to the commercial diesel, but the requirement for double the heat exchanger (or radiator) capacity of the diesel makes the Stirling engine appear to be unattractive for combat vehicles from an overall installed volume standpoint. The wide range of fuels which can be used in the Stirling engine could sometimes be useful, and the fuel consumption being lowest at mid to low power levels is well matched to combat vehicle requirements, but these advantages would appear to be far offset by the large volume requirement of the installed engine. While the volume of the Stirling engine can be reduced through advanced technologies which permit operation at higher temperatures and higher mean cycle pressures, the gains are not expected to be sufficient to offset the large current disadvantage. Indeed, current short-life, automotive Stirlings already operate at speeds and pressures comparable to uprated diesels; there is, therefore, little room for further uprating. Moreover, the same technologies which permit higher cycle pressures would also permit higher peak pressures in the diesel engine and correspondingly higher output.

2. Non-Combat Ground Vehicles

Non-combat vehicles of a wide variety are used in the Department of Defense. They are typically on and off highway trucks from one-quarter to 10 or more ton payload capability, ambulances, fire trucks, fork lifts, construction equipment, etc. In virtually all cases, the system and mission has a commercial counterpart, so that commercial items are used as available off the shelf or with some modifications. There have been some families of military engines developed in the past to try to achieve the benefits of standardization in tactical vehicles; however, it has been the general result that overall program economies are best achieved with off-the-shelf commercial engines which are well developed for commercial use, are available at low cost, and can be supported with widely available spare parts.

In order for the Stirling engine to be of interest in non-combat vehicles, it would have to offer either greater life cycle economies or provide some mission advantage which would warrant a special engine development, production, and support. Since a very large production base exists for efficient and durable diesel and gasoline engines which currently satisfy non-combat vehicle requirements, it is not likely that the Stirling engine could be

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competitive from the economic standpoint. No requirements are now known which so urgently need the advantages of the Stirling engine that a special development and procurement would be warranted. Therefore, it does not appear that there is incentive to further explore Stirling engine application to non-combat vehicles in the Department of Defense. If Stirling engines were commercially available, DoD would consider them in competition with other commercial engines.

3. Mobile Electric Power (MEP)

There are a wide variety of military needs for portable generation of electric power. In order to avoid proliferation of makes, models, and sizes, a DoD Standard Family of Mobile Electric Power Sets has been established from which all users of electric power in the field must choose to support their system requirements. This family is shown in Table 3. It will be noted that while the power range is 0.5 to 750 kw, the majority of sets are in the 1.5 to 60 kw range, with the smaller end of the range being most numerous. With the exception of the very small power range, all the engines used are commercially available diesel engines, and there is a desire to eliminate the gasoline engine sets altogether. The commercial diesel engine typically meets the performance requirements of MEP without significant penalty. The most important single characteristic of MEP engines is probably acquisition cost, since they are procured in large quantities, and therefore an established commercial base is of high significance.

Table 3. General Purpose Generator Sets in the US DoD Inventory

SIZE (kw)	AF ASSETS	NAVY ASSETS	MC ASSETS	ARMY ASSETS	TOTAL ASSETS
0.5	6	0	0	3,268	3,274
1.5	746	0	0	38,887	39,633
3	2,168	0	2,163	31,745	36,076
5	934	109	0	26,496	27,539
10	1,267	98	1,424	19,404	22,193
15	397	934	0	3,655	4,296
30	1,583	275	1,563	4,412	7,833
60	6,173	318	620	5,455	12,566
100	720	126	137	1,131	2,114
200	737	350	189	124	1,400
500	10	0	0	21	31
750	0	0	0	21	21
TOTALS	14,741	1,520	6,096	134,619	156,976

Source: NATO Exercise on Tactical Electric Power.

In addition to the standard battlefield power requirements, there are sometimes systems which have extreme mobility requirements or other urgent requirements of a nature

that cannot be satisfied by the Standard Military Family. In these special cases, special generator sets may be warranted. Turbine engines are probably the most common alternative to the standard diesel engine sets. In many weapons systems, the necessity for a high degree of mobility or portability is sufficiently important that special purpose sets are procured at a cost penalty in order to obtain low weight and size. Turbine generator sets are very much smaller and lighter than diesel sets, but have the disadvantage of higher fuel consumption and cost, making them inappropriate choices for general purpose sets.

Stirling engines cannot now be strong candidates for application to the DoD Standard Family of Mobile Electric Power Sets, due to the acquisition cost disadvantage compared to the high volume commercial diesel engine with its well established production base. A low signature, noise or other, is important in many MEP sets and the Stirling engine might offer an advantage in this respect. However, at this time, the most cost effective method of meeting the signature requirements is to provide a suitable housing or shelter for the standard diesel set. The other main advantage of Stirling engines may be their ability to function on a wide variety of fuels; however, this advantage seems of limited usefulness in general purpose applications where a standard fuel supply is available.

The Free Piston Stirling Engine (FPSE) is a variation of the Stirling cycle which has unique characteristics which may be of military interest. The characteristics of current engines are shown in Table 1. The version of particular interest is the hermetically sealed engine with linear alternators directly connected to the free pistons. This version eliminates the problem of leakage of the hydrogen working fluid, might be as light and efficient as other small engine generator sets, and offers very low noise and vibration levels. Due to the inability to precisely control the desired location of the work and displacer pistons, the FPSE may not have the potential for as high efficiency as the kinematic Stirling. There has not been significant development funding applied to the FPSE concept, so it is not as advanced in development as the kinematic Stirling, especially at part power. This engine would appear to offer the potential of satisfying the technical requirements for the Army's SLEEP ROC (Silent Lightweight Electric Energy Plants Required Operational Capability) in competition with muffled, sound-insulated diesels.

4. Auxiliary Power Units

Auxiliary power units are usually small engines under 100 horsepower which provide auxiliary power in the form of electricity, pneumatic energy, or hydraulic energy to the system in which it is installed. Applications include starting power for aircraft, standby

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or emergency electrical power, or other uses in systems not provided by the primary propulsion system. In aircraft, it is important that APUs be of light weight, and in combat vehicles it is important that the installed volume be small. In both cases, simple cycle gas turbines are typical choices. The Stirling cycle APU, as shown in the characteristics of Table 1, is neither low weight or low volume and is therefore not usually competitive with the turbine in these applications. If the requirement for power with low signature becomes quite important for silent watch for combat vehicles, the Stirling, and particularly the Free Piston Stirling Engine, may become of interest.

In general, if auxiliary power requirements are special in nature, such as in aircraft or combat vehicles, turbine engines are developed or adapted to use. Otherwise, if the requirement is not critical of weight and size, a commercially available piston engine will be more cost effective, the same as in other general purpose applications.

5. Small, Unmanned Submarines

The military need for small submarines ranges from tethered unmanned submersibles for underwater inspection to free-swimming vehicles that can carry a few people at a few knots for many hours. At least some of the applications are for surveillance and other missions that require very quiet operation.

Submarines, like other self-propelled vehicles that carry their own prime mover and fuel, have a total propulsion package weight and volume of engine plus fuel. For short duration missions, or more accurately, for missions with low total energy expenditures, the fuel weight is small, fuel efficiency is not very important, and the specific power of the engine dominates the total propulsion package weight and volume. For long duration missions, the fuel will dominate the total propulsion weight, fuel efficiency is very important and using a heavier engine to achieve it is worthwhile.

The Stirling engine has three *potentiai* advantages for submarine applications: high efficiency, insensitivity to heat source, and quiet operation.

This section considers Stirling engine applications in small unmanned submersibles. These vehicles have a variety of uses. Some applications, for example, inspection of underwater sections of off-shore oil rigs, are very short range and umbilical power could be provided. At longe ranges, the submersible must still, presumably, be connected by an umbilical to a mother ship for control and communication but optic fibers allow this communication range to be 10-20 kilometers--longer with repeaters.

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Transmitting power over that distance is impractical with an umbilical, and conducting wires could be detected. Nevertheless, the need for an umbilical communication connection probably constrains the required range to less than 100 km or so.

Besides range, another important mission factor is the speed of the vehicle. The maximum required power determines the engine size and required power increases as the cube of the speed. For a given range, the volume increases somewhat less quickly than the square of the cruising speed. If speeds are kept below 10 knots, then even torpedo-sized devices have ranges of up to 100 km using lead-acid batteries as the energy source.

In short, the high efficiency of the Stirling engine could be important for some long missions, but Stirling engines are not able to displace batteries--even lead-acid batteries-- from the unmanned submersible mission. According to *Underwater Power Sources* [Ref. 1], "There was no definite power requirement for small untethered [i.e., manned] submersibles that was unattainable because of present battery capabilities," and the unmanned submersible will probably be even less demanding. Moreover, there are other possible battery systems that have much higher energy storage than lead-acid and there is considerable room for improvement in the future. For example, silver-zinc batteries offer five times the energy density, and hence five times the range, of lead-acid batteries. Fuel cells offer even further room for improvement.

If the Stirling engine fails to justify itself on the basis of efficiency, then its other two advantages, being insensitive to heat source and being quiet, are relatively less important. Being insensitive to heat source gives the Stirling engine an advantage compared to open-cycle engines that use or produce gaseous products. In contrast, a Stirling engine can use a constant volume exothermic reaction, for example, sulfur hexafluoride on lithium, that generates no exhaust. However, this is not an advantage relative to *batteries*. Similarly, although the Stirling engine is quieter than other reciprocating prime movers it certainly is not quieter than batteries or fuel cells.

6. Space Power

The Stirling engine is being investigated as part of a space power system. The efficiency of a space-based power system is critical to the overall weight which is, of course, of primary concern for space operations. High efficiency decreases system weight in two ways. For any given output power, the more efficient the conversion system is, the less heat that goes in which means that smaller reactors or solar collectors can suffice. In addition, the higher the efficiency, the less waste heat there is to be rejected which reduces

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the size of the required radiator. Secondary effects can also be important, for example: higher efficiency means smaller heat storage masses are required to operate solar-power systems during eclipse and higher efficiency results in smaller reactors, and hence less radiation shielding for nuclear-powered systems.

Reliability is the other high priority for any space application. Typically, this translates into simplicity of design, few moving parts, some redundancy, and a system that does not fail catastrophically. Areas of special concern for reliability considerations are sliding seals, bearings, and vibration.

Photoelectric cells fill most current space power requirements. For larger power uses, nuclear-powered thermal electric generators are used. For still larger future power requirements, some form of dynamic power system will probably be required. The Stirling engine is potentially very efficient and reliable, making it an attractive dynamic system for space applications. The main competitor to the Stirling engine is the closed recuperative Brayton cycle engine. Both systems can operate in enclosed working gas environments to eliminate leakage, both can use gas bearings to essentially eliminate wear, both systems can operate at reduced pressure to maintain good efficiency at part power. The Brayton engine potentially has a single moving part containing the compressor, turbine, shaft, and alternator armature. The Stirling engine has two moving pistons per cylinder and at least two cylinders. The Brayton engine's turbomachinery has potentially very low vibration and the Stirling engine, with an arrangement of opposed cylinders, can balance the motion of the reciprocating pistons to achieve low vibration levels.

The Brayton cycle engine and the Stirling engine appear to be close competitors for the space power mission. However, turbomachinery has low efficiency in smaller sizes (remember that a "large" power user in space could be just a few hundred watts, quite small for a turbine). Where turbines suffer from low efficiency in the smaller power ranges, positive displacement engines have typically served so the positive displacement Stirling may be most appropriate in those power ranges that are too large for thermoelectric sources and require dynamic sources, but are too small for Brayton engines.

REFERENCE

1. *Underwater Power Sources*, UEG Publication UR32, UEG, 6 Storey's Gate, Westminster, London SW1P3AU (a part of CIRIA, The Construction Industry Research and Information Association), 1985.

Appendix A

SIZE AND SPECIFIC FUEL CONSUMPTION RELATIONSHIPS FOR STIRLING ENGINES

Written by:

Graham Walker*

SIZE AND SPECIFIC FUEL CONSUMPTION RELATIONSHIPS FOR STIRLING ENGINES

A. IDEAL ENGINE PERFORMANCE

### 1. Ideal Cycles and Mechanical Arrangements

a. Definition

A Stirling engine is a heat engine that operates on a closed thermodynamic regenerative cycle in which the flow of working fluid is controlled by volume changes. The working fluid experiences periodic compression at low temperatures and expansion at high temperatures, so there is a net conversion of heat to work. Stirling engines may be rotary or reciprocating machines.

Other machines, with superficial similarity to Stirling engines, operate on a regenerative thermodynamic cycle but are equipped with valves to regulate the flow of working fluid. Such engines may be called Ericsson cycle machines. None of the subsequent discussion relates to this class of engines.

b. The Ideal Cycle

The thermodynamic reference cycle of the ideal Stirling engine consists of two isothermal and two constant-volume phases, as shown in pressure-volume and temperature-entropy coordinates in Figure A-1a. An engine capable of operating on this cycle might conceivably consist of the elements shown in Figure A-1b, comprising a cylinder containing two opposed pistons and the regenerator. The space between the two pistons is the working space and is divided by the regenerator into two parts, which may be called the expansion space and the compression space. The expansion space is maintained at a high temperature T_h and the compression space is maintained at a low temperature T_c, so that there is a temperature gradient of T_h - T_c across the two transverse faces of the regenerator. The disposition of the pistons at the four terminal points of the cycle and the cyclic piston displacement-time diagram are shown in Figure A-1c. It should be noted that

REGENERATOR

EXPANSION SPACE / COMPRESSION SPACE
AT TEMPERATURE AT TEMPERATURE
T_h T_c

PISTON DISPLACEMENT

PHASE ANGLE a

TIME
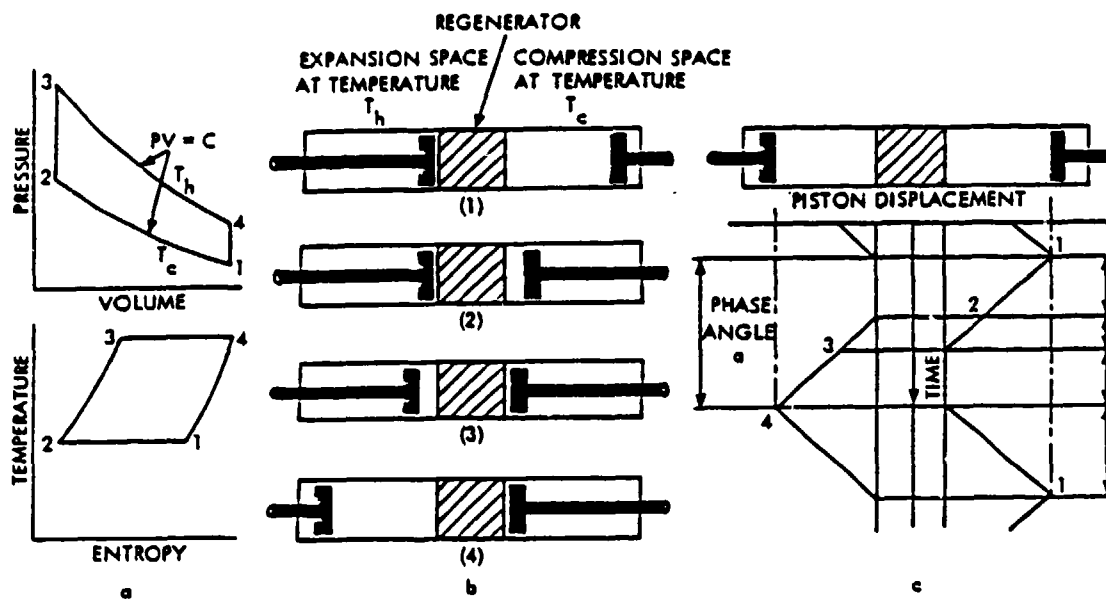
Figure A-1. Thermodynamic Cycle of the Ideal Stirling Engine

in the ideal machine the pistons have a discontinuous motion and that the expansion space piston leads the compression space piston by a phase angle α. If the machine acts as a refrigerator the operational cycle is precisely similar except that the temperature relation between the two spaces is reversed.

c. Practical Cycle

Practical Stirling engines normally comprise the same basic elements as the ideal engine with the addition of a heat exchanger at each end of the regenerator. In most engines the volumes of the compression and expansion spaces are varied in an approximately sinusoidal manner. This results in a pressure-volume diagram that is a smooth, continuous envelope in which the four phases discussed above are merged. Since the compression and expansion of the working fluid do not now take place wholly in one or the other of the two spaces, three pressure-volume diagrams may actually be drawn: one for the expansion space, one for the compression space, and one for the total enclosed volume, which includes the dead space. The dead space may be defined as that part of the working space not swept by one of the pistons, and it includes the internal volume of the heat exchangers, the void volume of the regenerator, and the volume of associated connecting ducts and ports.

A-2

A further important heat exchanger necessary to the system when utilizing combustion heat is the exhaust-gas heat exchanger. This may be of the regenerative or recuperative type. It is a necessary component to extract from the hot combustion gases as much energy as practicable. Losses to the exhaust in a Stirling engine are a direct deduction of the energy available for conversion, since the energy of the exhaust bypasses the engine. (In the case of *internal* combustion engines the exhaust energy has already passed through the engine conversion system.) As a consequence of this, all the heat rejected from the system, apart from the exhaust stack loss, must be transferred through the cooling system. Thus the cooling system for Stirling engines is approximately twice the capacity of the cooling system of internal combustion engines of the same power output.

d. Possible Engine Arrangements

All existing designs of single-cycle reciprocating Stirling engines may be broadly classified into two groups: (1) two-piston machines and (2) piston-displacer machines. A further subdivision can be made in this group between machines in which the piston and displacer operate in a single cylinder and those in which separate cylinders are provided for the displacer and the piston. An example of each of these three arrangements is shown in Figure A-2. It is now generally recognized that the best possible configuration for engines operating at high speeds and at high-pressure levels is probably the single-cylinder piston-displacer type. This arrangement allows for compact design with minimum mechanical and flow losses and can be adequately balanced mechanically. It is interesting to note that this was the arrangement used in the original engine built in 1816 by Stirling, who later went on to build engines with separate cylinders for the piston and displacer.

For high-power, multiple-cylinder engines it is possible to mount several single-cycle engines on a common crankshaft. However, the preferred alternative is to use the Rinia arrangement shown in Figure A-3. This reduces the number of reciprocating elements per cylinder to one, half the number required in the multiple single-cylinder case.

2. Ideal Cycle Performance

The cycle performance can be characterized by the thermal efficiency and various measures of specific power output (power output per unit mass flow in the cycle or power output per unit volume), as will be discussed subsequently. For convenience, two ideal cycles are considered here: (1) the ideal Stirling cycle, as depicted in Figure A-1, and (2) an idealized version of the practical Stirling cycle, which incorporates sinusoidal piston and
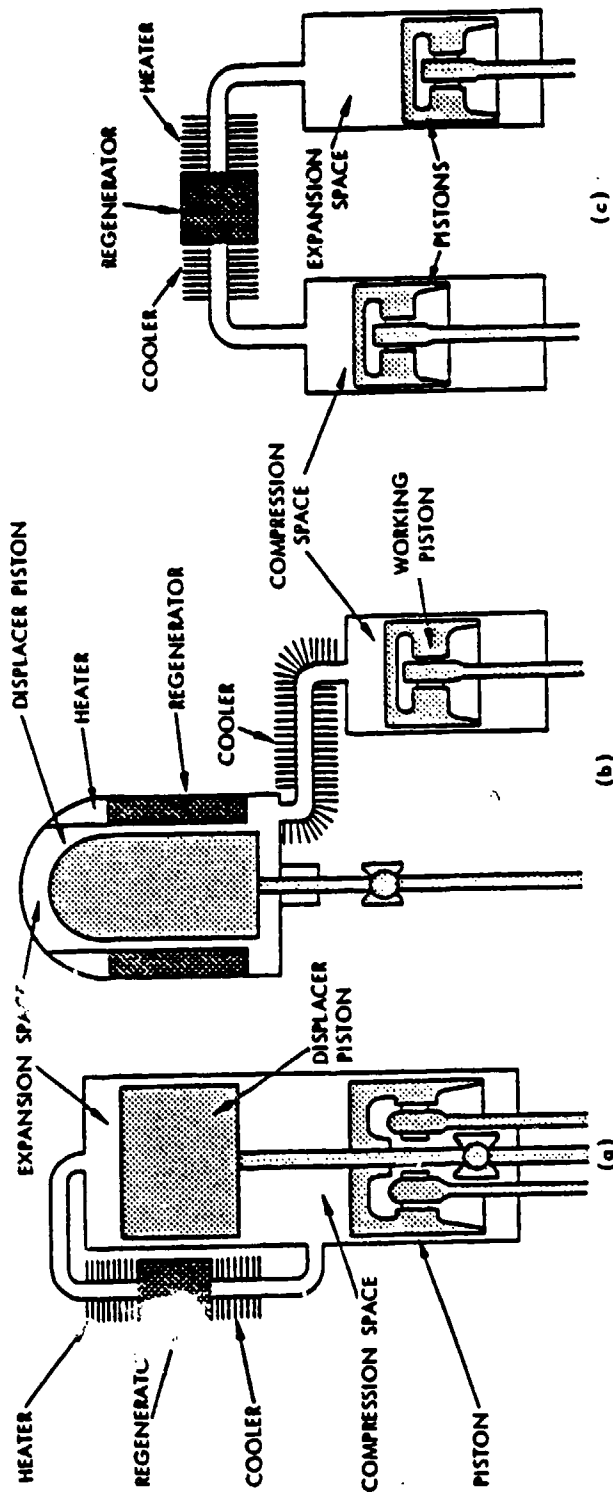
Figure A-2. Basic Mechanical Arrangements for Single-Cycle Stirling Engines

(In machines combining a working piston and a displacer piston, which helps to move the gas back and forth between the compression space and the expansion space, the two pistons can be in the same cylinder (a) or in separate cylinders (b). The third basic arrangement (c) is a two-piston Stirling engine.)
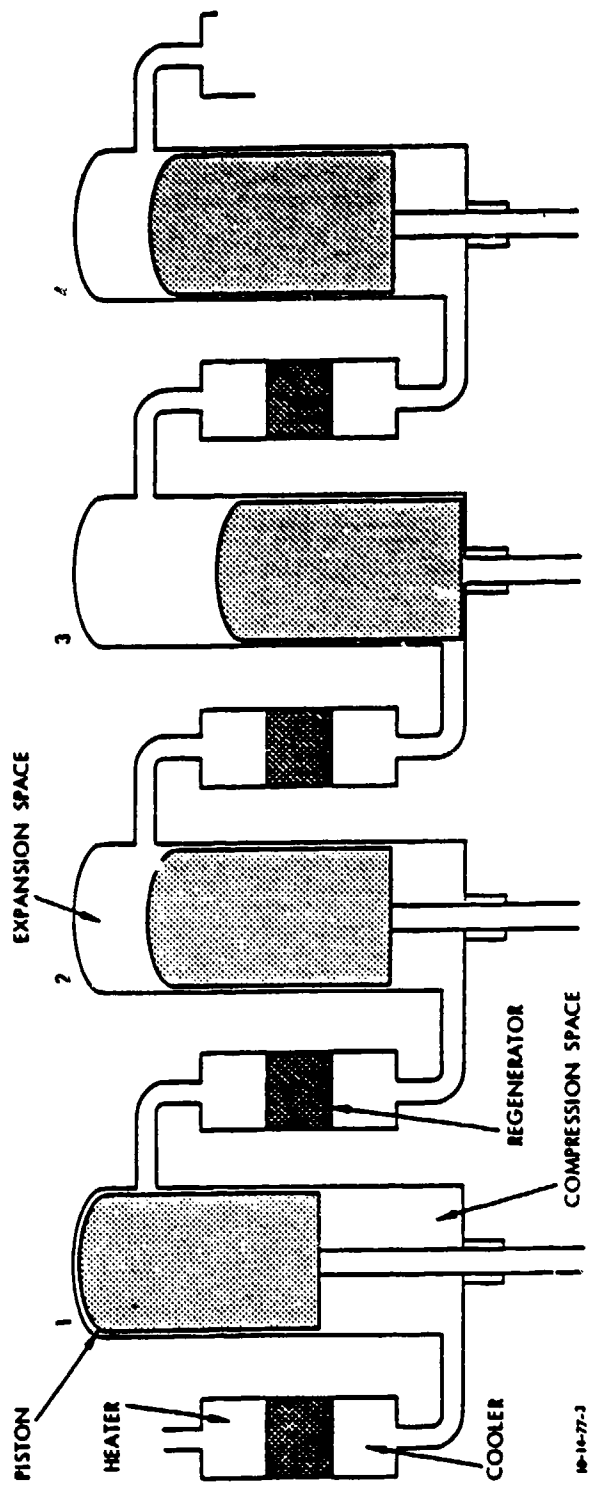
Figure A-3. Rinia Arrangement of a Multicylinder Stirling Engine

(The arrangement was devised by Herre Rinia of the Philips Research Laboratories in the Netherlands. Adjacent cylinders are interconnected through a regenerator. With this arrangement there is only one reciprocating element per cycle, rather than two elements as in single-cylinder engines.

A-5

displacer motion, and inactive internal volumes associated with heat exchangers and clearances, but is ideal in the sense that internal losses are assumed to be absent.

a. Performance of the Ideal Stirling Cycle

The thermal efficiency of the ideal Stirling cycle is simply the Carnot efficiency, i.e.,

$$\eta = \frac{T_h - T_c}{T_h}$$ (Eq. A-1)

This is due to the isothermal compression and expansion processes, which result in all heat addition at the maximum cycle temperature T_h and all heat rejection at the minimum cycle temperature T_c. Increase in the upper cycle temperature cr decrease in the lower cycle temperature will result in an increase in the cycle efficiency as shown in Figure A-4. Two curves are shown in this figure. One curve shows the effect on cycle efficiency with variable minimum cycle temperature and constant maximum cycle temperature. The other curve shows the effect on cycle efficiency with variable maximum cycle temperature and constant minimum cycle temperature.

The specific power of the ideal Stirling cycle can be expressed as

$$\frac{P_o}{\dot{m}} = \eta \frac{P_{add}}{\dot{m}} \ ,$$ (Eq. A-2)

where

P_o = output power

$\dot{m}$ = cyclic mass flow rate

P_{add} = heat addition rate.

For the ideal cycle, the heat addition rate is

$$P_{add} = \dot{m} \, R \, T_h \, \ln r \ ,$$ (Eq. A-3)

where R is the gas constant and r is the compression ratio (ratio of maximum to minimum volumes). The power output per unit volume is obviously proportional to the product of the density, engine speed, and the power output per unit mass flow rate.

A-6
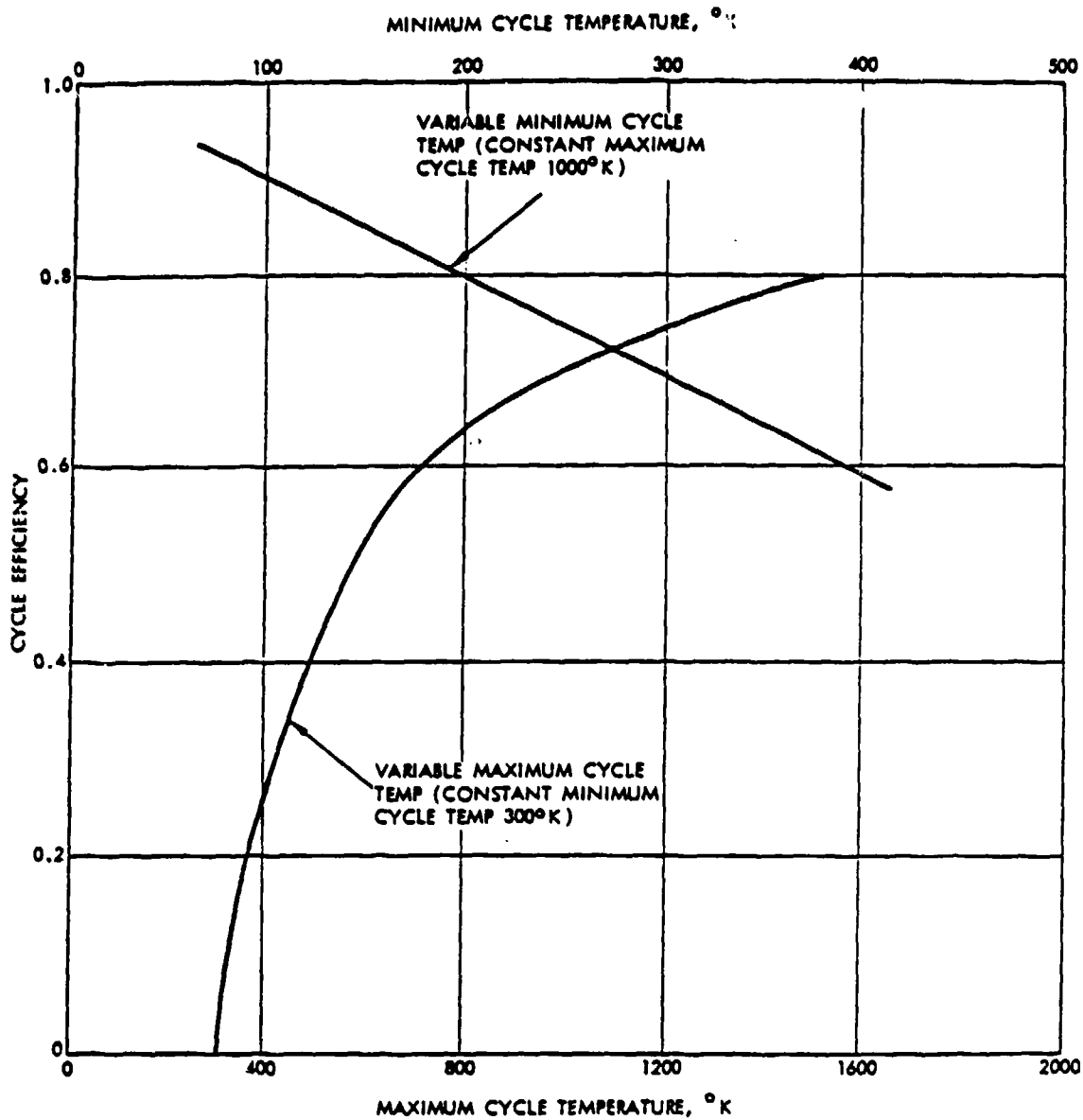
Figure A-4. Effect of Maximum and Minimum Cycle Temperature on Ideal Efficiency

The basic cycle parameters affecting specific power are then:

(1) Temperature limits of the working fluid,

(2) Pressure of the working fluid,

(3) Speed of operation of the engine.

The effect of temperature on engine power output can best be seen by reference to the pressure-volume and temperature-entropy diagrams for the ideal Stirling cycle shown in Figure A-5. In these diagrams, area 1-2-7-8 represents the energy supplied to the cycle.
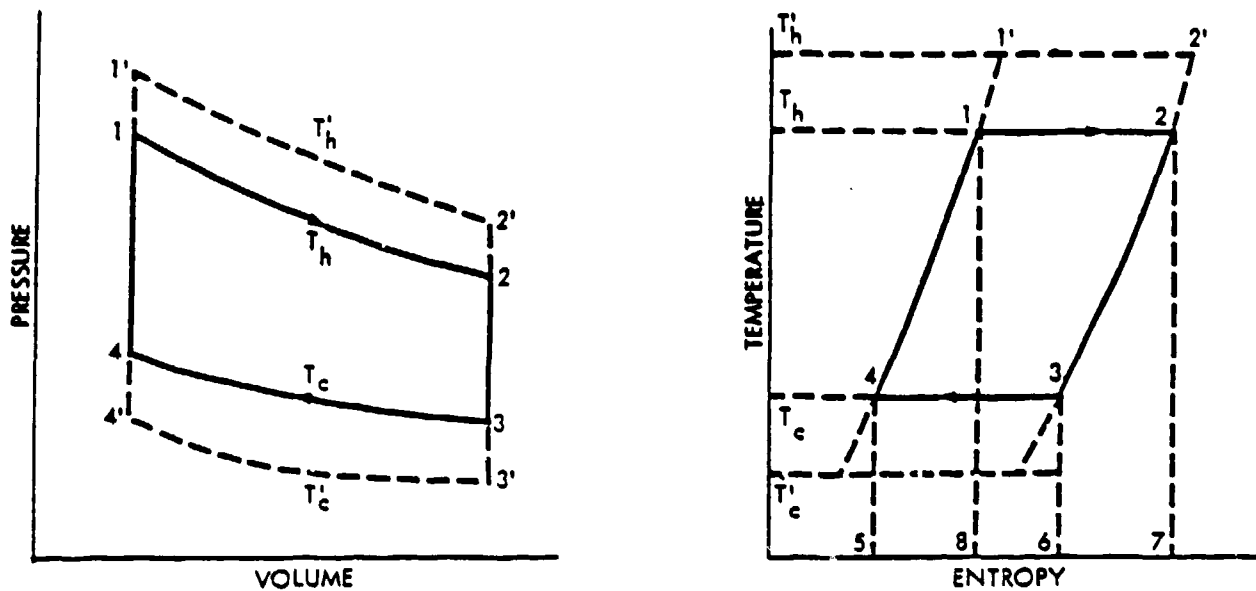
Figure A-5. Pressure-Volume and Temperature-Entropy Diagrams of Ideal Stirling Cycle, Illustrating Effect of Variation in Cycle Temperature Limits

Area 3-4-5-6 represents the heat rejected from the cycle, and area 1-2-3-4 represents the work output of the cycle. Increase in the upper cycle temperature to the T_h' increases the work output by the area 1-1'-2'-2. Similarly, decrease in the minimum cycle temperature from T_c to T_c' increases the work output by the area 4-3-3'-4'.

Improvements in efficiency and specific output are progressive with separation of the upper and lower cycle temperatures. Practical limits are imposed, however, at the top temperature by the metallurgical limits of the materials used for the heated regions, and at the low temperature by the cooling media available for use in the engine. If a conventional water-cooled radiation system is used, the low-temperature limit is then controlled by the capacity of the radiator cooling system.

Specific power of the engine is related in linear fashion to both the pressure of the working fluid and the speed of operation. Increase in either (or both) causes a corresponding increase in the power output of the engine.

A-8

b. Ideal Performance of a Practical Cycle

The ideal performance of a practical cycle, which includes continuous, rather than discontinuous, motions of the pistons and/or displacers, and which contains appropriate clearance and heat exchanger volumes, is influenced by several factors:

(1) The ratio of the mean temperature levels in the expansion or compression spaces, denoted by τ.

(2) The form of the variations in the volumes of the two spaces. In most cases, this is nearly simple harmonic.

(3) The ratio between the swept volumes in the two spaces, denoted by κ.

(4) The angular phase displacement by which the expansion space leads the compression space, denoted by α.

(5) The clearance volume which remains in either space when the volume of that space is reduced to a minimum. This may frequently be included in:

(6) The "dead" volume of the heat-exchanger transfer passages and the void volume of the regenerator. This may be compared with the maximum volume in the expansion space and the ratio denoted by χ.

(7) The mean pressure level in the working space p_m.

(8) The range and the nature of the variation in pressure of the working fluid during the cycle. This depends on the temperature and volume variations and so is not independent. Often, however, it is comparatively easy to measure, and so this becomes an important parameter.

(9) The speed of the engine.

(10) The physical characteristics of the working fluid.

A theory in which the pistons are assumed to move with simple harmonic motion, and which indicates the influence of the above parameters, was developed by Schmidt [Ref. A-1] and has become the classical analysis of the cycle. The major assumptions made are that the temperatures of the working fluid in the compression and expansion spaces remain constant, that the regenerative process is perfect, and that there are not internal losses.

The efficiency of cycle remains the Carnot efficiency, again due to the assumptions that all heat addition is accomplished at the maximum cycle temperature, all heat rejection is accomplished at the minimum cycle temperature, and there are no other losses.

The basic equation developed by Schmidt for the work output of a Stirling engine is

A-9

$$P = (1 - \tau) Q_h = (1 - \tau) \pi p_m \frac{V_E \delta \sin \theta}{1 + (1 - \delta^2)^{\frac{1}{2}}} , \qquad \text{(Eq. A-3)}$$

where

P = work output per cycle

τ = temperature ratio T_c/T_h

Q_h = heat added per cycle

p_m = mean pressure during cycle

V_E = volume of the expansion space

$$\delta = \frac{(\tau^2 + \kappa^2 + 2\tau\kappa\cos\alpha)^{\frac{1}{2}}}{\tau + \kappa + [4\kappa\tau/(\tau + 1)]}$$

θ = $\tan^{-1} [(\kappa\sin\alpha)/(\tau + \kappa\cos\alpha)]$.

The power output is merely

$$P_o = P \omega , \qquad \text{(Eq. A-4)}$$

where ω is the cyclic rate.

Equation A-3 expresses the ideal output in terms of the four cycle parameters τ, κ, χ, and α. It is convenient to render this equation nondimensional to examine the influence of these parameters on specific output.

The process to make the power equation nondimensional may be carried out in a number of ways. On a basis of unit mass of working fluid, the power equation becomes

$$\frac{P}{mRT_c} = \frac{\kappa(1 - \tau) \delta \sin \theta (1 + \delta \cos \theta)}{(1 - \delta^2)^{\frac{1}{2}} [1 - (1-\delta^2)] (\tau + \frac{\kappa}{2} (1 + \cos \alpha) + \delta)} . \qquad \text{(Eq. A-5)}$$

The power equation may also be considered on a basis of some arbitrarily selected pressure and volume. Here the volume V_T used throughout is the sum of the maximum volumes in the expansion and compression spaces. The pressure may have any value, and here the maximum p_{max}, the minimum P_{min}, and the mean p_m cycle pressures have been used. The corresponding equations then become

$$\frac{P}{P_{max}V_T} = \frac{\pi(1-\tau)}{1+\kappa}\left(\frac{1-\delta}{1+\delta}\right)^{\frac{1}{2}} \frac{\delta}{[1+(1-\delta^2)^{\frac{1}{2}}]}\sin\theta \qquad \text{(Eq. A-6)}$$

$$\frac{P}{P_{min}V_T} = \frac{\pi(1-\tau)}{(1+\kappa)}\left(\frac{1+\delta}{1-\delta}\right)^{\frac{1}{2}} \frac{\delta}{[1+(1-\delta^2)^{\frac{1}{2}}]}\sin\theta \qquad \text{(Eq. A-7)}$$

$$\frac{P}{P_m V_T} = \frac{\pi(1-\tau)}{(1+\kappa)} \frac{\delta}{[1+(1-\delta^2)^{\frac{1}{2}}]}\sin\theta \ . \qquad \text{(Eq. A-8)}$$

Obviously, many thousands of different combinations of the four design parameters τ, κ, χ, and α are possible, and the work of optimization has been facilitated by the use of a digital computer. Some characteristic results are given in Figure A-6. Each of the four separate sets of curves shows the effect on the engine power with variation in one of the design parameters. The values of the other three are fixed as indicated beneath each of the graphs. For reference the pressure ratio is also shown for the four sets of results. This has the unique value for any given combination

$$\frac{P_{max}}{P_{min}} = \frac{1+\delta}{1-\delta} \ . \qquad \text{(Eq. A-9)}$$

Reference to Figure A-6 shows that the engine power output is not greatly sensitive to the phase angle α but does tend to reach a maximum value in the vicinity of 90 degrees.

B. RELATIONSHIP OF ACTUAL PERFORMANCE TO IDEAL PERFORMANCE

The subsystems of a Stirling engine include five basic, internally linked units:

(1) Expansion space

(2) Heater

(3) Regenerator

(4) Cooler

(5) Compression space.

A-11
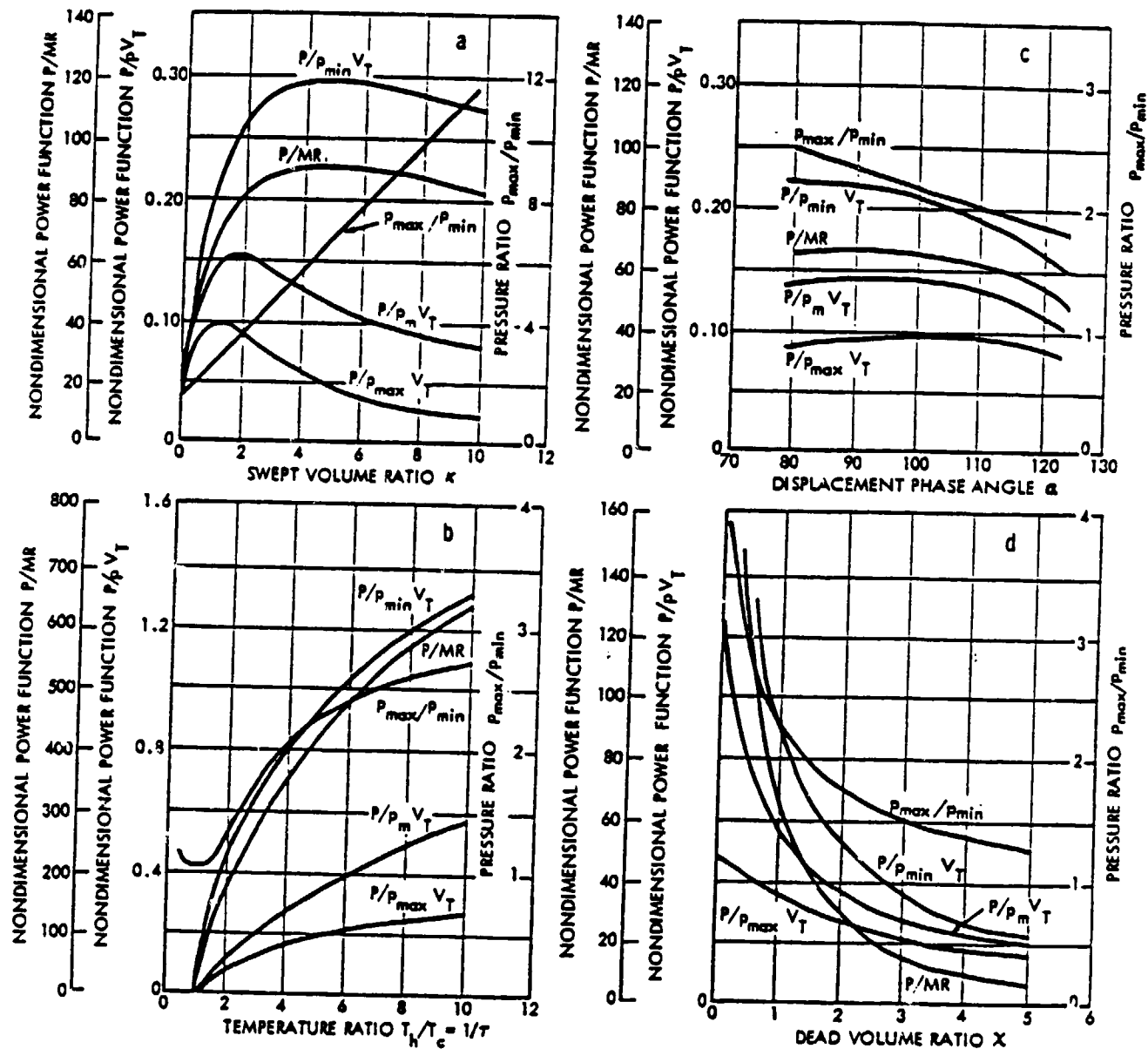
The power has been made nondimensional on four different bases. It should be noted that the optimum value of K or α depends upon the base selected.

a: $T = 0.5$; $\alpha = 90°$; $X = 1.0$ b: $T = 0.5$; $K = 1.0$; $X = 1.0$
c: $K = 1.0$; $\alpha = 90°$; $X = 1.0$ d: $T = 0.5$; $K = 1.0$; $\alpha = 90°$

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Figure A-6. Variation in the Nondimensional Power and Pressure Ratio With Change in the Four Main Design Parameters According to the Schmidt Isothermal Analysis

A-12

The working fluid is distributed throughout the five subsystems. The distribution varies in cyclic fashion as the volumes of the expansion and compression spaces vary in a cyclic but out-of-phase fashion. The actual performance of Stirling engines depends upon the detailed behavior of the fluid in the five subsystems, and the complexity of this behavior has thus far hampered efforts to associate losses with the individual subsystems and to quantify their impacts on engine performance. As examples of the complexities involved, Figure A-7 shows the cyclic pressure variations measured in the expansion and compression spaces of a Stirling engine acting as a refrigerating machine, and Figure A-8 shows the variation of mass flow rates in and out of the compression and expansion spaces of the same machine.

The major factors affecting the actual performance of a practical Stirling cycle (as opposed to the ideal performance) are:

(1) The nature of the expansion and compression processes. At any instant these are probably adiabatic, but the issue is complicated by the fact that particular particles are generally moving to and from regions at different temperature levels.

(2) The range and the nature of the variation in the temperature in either or both of the working spaces throughout the cycle.

(3) The heat transfer and flow characteristics of the heat exchangers.

(4) The effectiveness of the regenerator.

Theoretical efforts subsequent to those of Schmidt have endeavored to account for some of these factors. Other workers, notably Zeuner [Ref. A-2] and Grashof [Ref. A-3], introduced variations of the Schmidt analysis, but the next major contribution to the theory was made by Finkelstein [Ref. A-4]. In this analysis it is possible to allow for a variation in the temperature of the working fluid when it is in the two working spaces. The two cases of interest initially are those in which the processes taking place in the expansion and compression spaces are (1) isothermal and (2) adiabatic, but it is possible to allow for any assumed variations between these limits. In the isothermal case, Finkelstein's final equations have closed solutions and can be reduced to a form identical with those of Schmidt, thus tending to confirm the logic of the analysis. Considerable complexity is introduced into the analysis when one allows for the fact that the processes taking place in the expansion and compression spaces may not be isothermal. Thus, the analysis treats nonisothermal compression and expansion processes, but even so a number of
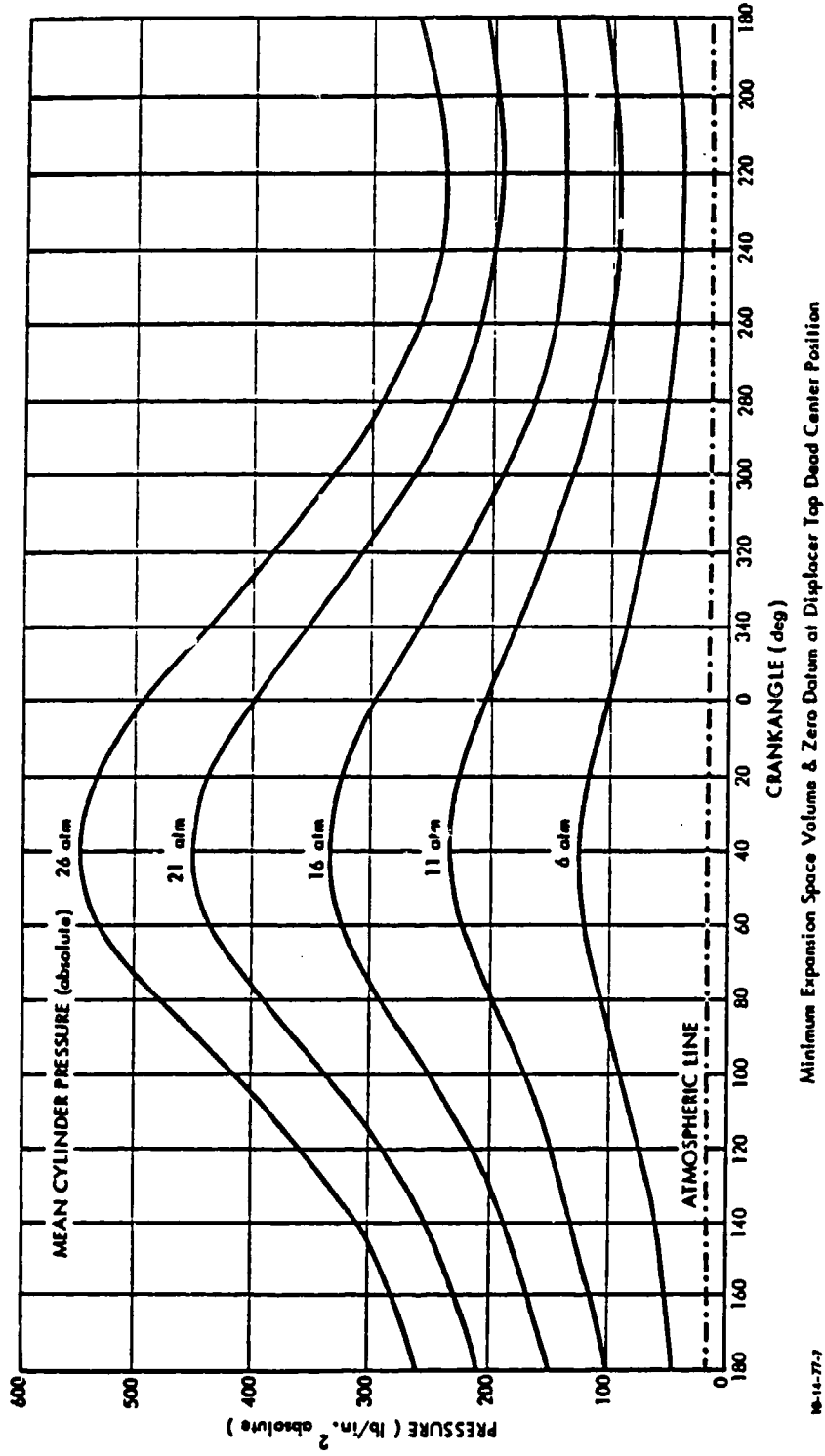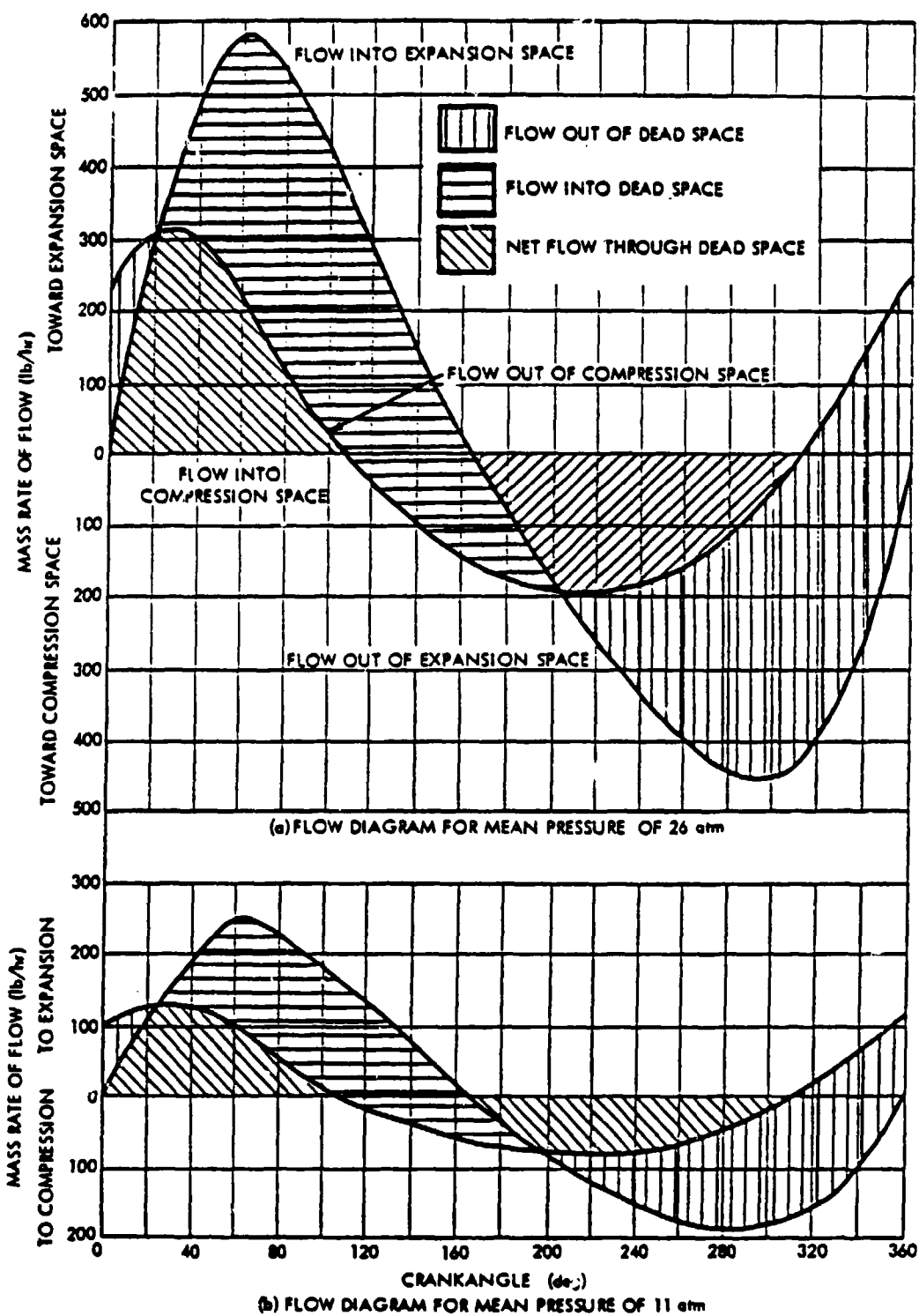
A-13

Figure A-7. Indicator Diagram Showing Cyclic Pressure Variation in Compression Space of Gas Refrigerating Machine Running at 1,450 rpm and With Different Mean Pressures of the Working Fluid (Hydrogen)

A-14

Figure A-8. Cyclic Mass Rate-of-Flow Diagrams for Gas Refrigerating Machine

A-15

assumptions are made. These are summarized below in order to show the extent of unrealism in what is the best available theory at the present time. It is assumed that

    (1) The regenerative process is perfect.

    (2) The instantaneous pressure is the same throughout the system.

    (3) The working fluid obeys the characteristic equation $PV = RT$.

    (4) There is no leakage and the mass of working fluid remains constant.

    (5) The volume variations in the working space occur sinusoidally.

    (6) The heat exchangers function perfectly.

    (7) The cylinder-wall and piston-head temperatures are constant.

    (8) There is perfect mixing of the cylinder contents.

    (9) The temperature of the working fluid in the ancillary spaces is constant.

    (10) The speed of the machine is constant.

    (11) Steady state conditions are established.

Of these assumptions it is suggested that 1, 2, 3, and 6 are those most worthy of further analytical attention.

Advanced analysis of Stirling engines is invariably accomplished by the operation of computer simulation models that generate specific numerical data rather than the generalized relationships common to other forms of prime mover based on units of mass or volume. Thus, providing such generalized relationships for a Stirling engine would be highly speculative at present, and no attempt to do so is made here.[1] Experience in the interpretation of the results of computer simulation studies, supported by both experimental and other theoretical work, has, however, permitted the importance of some of the loss mechanisms to be assessed. These losses may be arranged in three groups:

    (1) Nonisothermal compression and expansion processes

    (2) Aerodynamic flow friction and mechanical friction losses

    (3) Imperfect regeneration.

Isothermal compression and expansion processes require infinite rates of heat transfer between the cylinder walls and the working fluid. Clearly this is not attainable in a practicable machine operating at some reasonable speed (up to 5,000 rpm). Recent studies

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[1] [Editor's Note: A crude attempt at portraying the actual performance of Stirling engines in terms of energy transfers and loss characterizations has been made in the annex to this appendix.]

have been made of the effect in machine performance of zero heat transfer in the cylinders and infinite heat transfer in the heater and cooler units. This is thought to be close to the practical case. The results show that the temperature of the working fluid in the cylinders experiences considerable variation, as shown in the specimen case (Figure A-9). The result of the temperature variation is to change the mass distribution in the machine and, as a consequence, to reduce very substantially the work *output* from the *expansion* space while the work *input* to the *compression* space remains about the same. The effect, of course, is to reduce the net output from the engine by up to 40 percent. Other theoretical work supports this evaluation of the magnitude of the losses associated with nonisothermal compression and expansion processes.
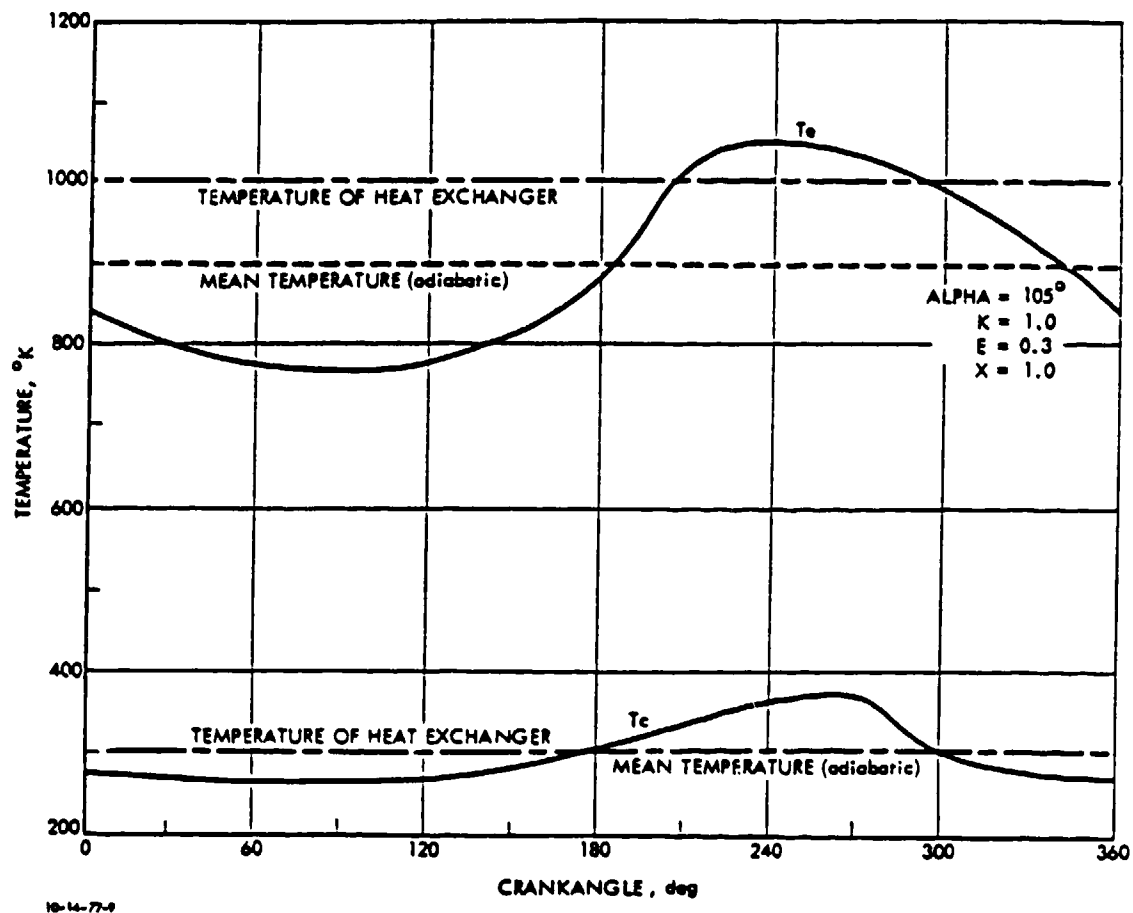
Figure A-9. Working Fluid Temperature vs. Crankangle for Stirling Engine With Adiabatic Compression and Expansion Spaces

A-17

In considering the case of a refrigerator, Finkelstein found that the coefficient of performance was reduced from 1 with isothermal processes to 0.543 with adiabatic processes. Later, Stoddart [Ref. A-5] found that the efficiency of an engine was reduced from 50 percent with isothermal processes to 34.3 percent with adiabatic processes. The failure of a practical engine to attain isothermal processes of expansion and compression appears to be the prime cause of the relatively disappointing testbed performance of Stirling engines compared with ideal cycles.

The effects of aerodynamic flow losses are illustrated in Figure A-10. This shows typical work diagrams for a Stirling engine, including diagrams for the expansion space, compression space, and total working space. The diagram for the expansion space is formed by tracing the pressure-volume variations in the expansion space in a clockwise direction. The area of the diagram is positive (output) work. The diagram for the compression space moves in the reverse direction. The area of the diagram is negative (input) work. The difference between these diagrams is net output of the engine.
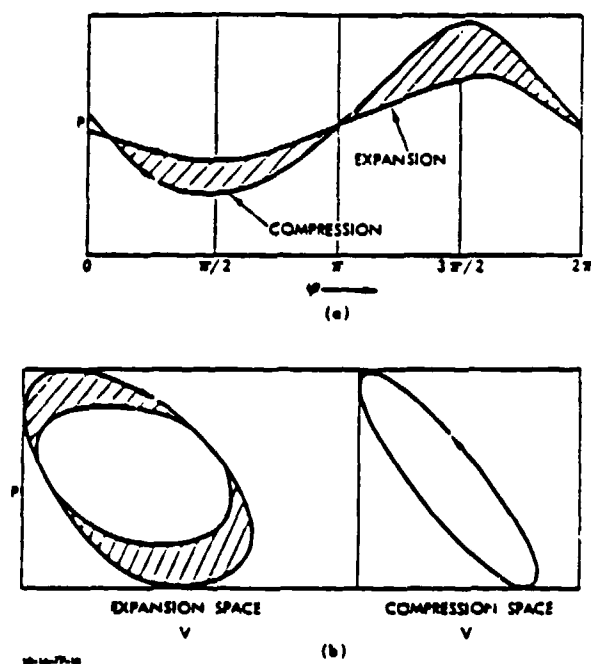
Figure A-10. Effect of Aerodynamic Flow Loss on the Work Diagrams of a Stirling Engine

Aerodynamic friction is manifest principally in the finely divided metallic matrix of the regenerator and to a lesser extent in the fine-bore tubes or fin-slots of the heater and cooler. The effect of the aerodynamic friction is to cause a difference in pressure between

A-18

the working fluid in the compression and expansion spaces. The range of pressure variation in the compression space is increased, while the range of pressure variation in the expansion space is decreased. As shown by the shaded areas in Figure A-10, this causes an *increase* in compression work and a *decrease* in expansion work. Both effects combine to diminish the available net engine output.

Mechanical friction in the engine arises from action of rubbing seals on pistons and rods or from bearing and windage in the crank mechanism. Typically, in a good engine design 15 to 20 percent of the available net engine output may be absorbed by mechanical friction.

Losses due to imperfect regeneration arise from the existence of finite rates of heat transfer between the working fluid and the regenerative matrix material. This causes the regenerator to function less effectively than the ideal case, where infinite rates of heat transfer are assumed. An adequate theory for the operation of a regenerative heat exchanger in a Stirling engine has not yet been developed. Therefore, it is not possible to quantify the effects of imperfect regeneration. Experience has shown that the regenerator is more significant in Stirling engines used as cryogenic cooling engines than in Stirling engines used as prime movers. In advanced engines, however, the regenerator is a key component of the system, and much engineering development effort has been expended in optimizing the balance between better heat transfer and minimizing aerodynamic friction. Much of the best research work on regeneration has been carried out in the research laboratories of Philips in Eindhoven, the Netherlands, and has not been published in the open literature.

C. OVERALL ENGINE CONSIDERATIONS

1. Efficiency and Specific Power of Actual Stirling Engines

There are no Stirling engines in commercial production apart from (1) those produced, mainly by the Philips Company, Eindhoven, for cryogenic refrigerators; (2) demonstration free-piston Stirling engines produced by Sunpower, Inc., Ohio; and (3) laboratory demonstration engines made by Leyhold-Heraeus in West Germany.[2]

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[2] This was the situation in 1978. Appendix B assesses the current state of Stirling engine developments.

Very substantial research and development effort on Stirling engines for automotive application has been invested over the past decade by Philips and their licensees, including:

- General Motors, USA, from 1958 to 1970
- United Stirling, Sweden, since 1968
- M.A.N./MWM, West Germany, since 1968
- Ford Motor Company, USA, since 1971.

References A-6 through A-9 summarize the progress of Philips and their licensees. None of the engines discussed therein can be considered as production versions of automotive engines. The general target is to develop power units having compatible efficiencies and specific outputs to internal combustion engines. Table A-1 is a compilation of data on existing Stirling engines and is from Reference A-9.

2. Physical Limits of Performance

At the present stage of experimental development on theoretical understanding of Stirling engines, it is not possible to define the physical limits of subsystem or component performance.

Despite the magnitude and intensity of the Philips' effort over the past 30 years, the total investment in research and development effort in Stirling engines is virtually negligible compared with the investment in spark-ignition or compression-ignition engines. It is likely that a multitude of alternative concepts and variants await exploration. Two examples of recent innovations include the free-piston Stirling engine developed by Professor Beale at the University of Ohio and the use of two-phase/two-component working fluids under investigation at the University of Calgary. There appear to be many opportunities in this field for innovations and improvements.

Cost is perhaps the principal impediment to increased application of the Stirling engine. The cost arises from the multiplicity and the complexity of the heat-exchange equipment. Novel and innovative approaches to accomplish the necessary heat-transfer functions at significantly lower cost of materials or fabrication would expand the likely range of applications. The development of ceramic components may allow the use of higher maximum temperatures with consequent gains in both thermal efficiency and specific output. The applications of ceramic units is being actively pursued by several research and development groups.

Table A-1. Stirling Engine Characteristics[*]

Manufacture	Philips 4-215	Philips	United Stirling	GMRL GPU-3	Philips 4-235	Philips 40 hp	United Stirling	MAN-MWM 4-400
Status	Proto (Ford)	Analy. (opti-mized)	Proto	Proto	Proto	Proto	Analy. phase I	Proto
Type	Two piston	Piston-disp	Two piston	Piston-disp	Piston-disp	Piston-disp	Two piston	Piston-disp
Working fluid	H_2	He	H_2	H_2	He	H_2	H_2	H_e
Max press. F, psi	2350	3200	2100	1000	3200	2058	2100	1570
No. of cylinders	4	4	4	1	4	1	8	4
Max bhp	170	275	49	11	200	40	200	120
RPM at max power,	4000-4200	1600	3400	3600	3000	1500	2400	1500
Max torque, ft-lbs	300	1287	120	19	253	108	520	475
RPM at max torque	1400	400	955	1200-2400	1000	900	600	700
Gas temp (hot), °F	1300	~1400	1275	1400[a]	1260	1200	1325	1170
Gas temp (cold), °F	175	160	160	180	108	~0	160	105
Efficiency at max BHP (%)	24	30	24	25	30	30	30	29
Max efficiency, %	32[b]	43[b]	30	26.5[b]	31	38	35	32
Power at max efficiency, BHP	75	100	35	~7	175 (approx)	23	76	88
RPM at max efficiency	1100-2000	600	2000	1900	1800	725	1200	1000
Weight,[c] lb	750	N/D	N/D	165[d]	1272	N/D	1435	N/D
Dimensions,[c] ft.	N/D	4.9 x 4.3 x 2.2	N/D	1.3 x 1.3 x 2.4[e]	4.1 x 1.7 x 3.6	N/D	3.7 x 2.7 x 3.1	5.0 x 2.3 x 4.5
Applications	Auto	Bus	Auto	EPS	Bus	LRE	Bus, truck	LRE
References	6-6, 13, 22, 27	6-5	6-25, 28	6-3, 26, 38	6-39	6-8, 10	6-25	6-24

[a]Heater tube wall temperature.

[b]Net brake efficiency accounting for all auxiliaries including cooling fan, combustion blower, and water pump, among others.

[c]Includes all auxiliaries except cooling system with fan and transmission.

[d]Engine and auxiliaries less electrical power generator.

[e]Engine only.

Abbreviations:

   Proto: operating prototype engine; LRE: Laboratory Research Engine; Analy: computer design projection; N/D: no data; EPS: electric power supply.

[*] Source: Reference A-9.

The high-capacity cooling systems required by Stirling engines have spurred the development of improved "folded-front" radiator systems for automotive application. However, this same technology can also be applied directly to water-cooled internal combustion engines, so the favorable comparison of Stirling engines to internal combustion engines remains. It is worth noting that the cooling problem disappears in a marine environment. It is likely that Stirling engines may find marine applications where silent operation or the ability to operate on isotope heat or unconventional chemical reaction energy is of value.

To gain a high specific output it has been necessary to use helium or hydrogen as the working fluid at pressures of several thousand pounds per square inch. This has made the seal problem particularly acute. Much internal development on seals has been carried out by Philips and its licensees. A promising approach was the development by Philips of the roll-sock seal [Ref. A-9]. This provides a hermetic seal between the high-pressure working fluid and an equally high-pressure hydraulic "reservoir." In this way, the problem of the pneumatic seal is converted into a problem of hydraulic sealing. The viscosity of gas to oil is such that the hydraulic seal is comparatively easy to accomplish. However, the integrity of the roll-sock seal has yet to be adequately demonstrated for the life considered routine for heavy traction motors. Further, the system is relatively complicated and a simpler, more reliable system is preferred.

One possibility still in the early research stage is the use of a working fluid composed of two components, one of which experiences a phase change from liquid to vapor when passing from the cold compression space to the hot expansion space. This has the effect of increasing the virtual compression ratio of the engine. Calculations made using a modified Schmidt analysis indicate that the specific output may be double that attainable with a conventional gaseous working fluid. This work is at a preliminary, laboratory stage of experimentation and has yet to be demonstrated on an operational prototype engine.

The possibilities are so broad and the field is so virtually unexplored, except in certain narrow specialized areas, that excellent opportunities exist for original and innovative contributions to the technology of Stirling engines. It is likely that engines could eventually be developed with efficiencies and specific outputs up to 50 percent greater than existing prototype units.

3. Advantages and Disadvantages of Stirling Engines

The principal advantages of Stirling engines when used as prime movers generating power from heat supplied are:

(1) The peak efficiency and part-load performance are comparable with diesel engines.

(2) The engine can use any source of external heat, in particular, combustion of any fossil fuel.

(3) There are no valves or periodic explosions, so the engine operates virtually without noise.

(4) The vibration level is very low.

(5) The starting torque and torque/speed characteristic is favorable for traction applications.

(6) The combustion products are not in contact with the moving parts, so the engine has the potential for long life with minimum wear and virtually zero consumption of lubricating oil.

(7) The engine can be used for vehicle braking with negative torques up to 80 percent of the full-load torque.

(8) The engine has a fast response and can accept sudden changes in the load.

(9) It is not affected by a dusty or contaminated environment.

(10) The engine starts reliably and has the potential for a low maintenance requirement.

(11) Combustion takes place externally and continuously in a chamber with heated walls, so the unburned hydrocarbon content of the exhaust is very low. By recirculation of a sizable fraction of the exhaust, the oxides of nitrogen in the exhaust can be drastically reduced. In such form the engine can achieve the lowest degree of air pollution yet demonstrated.

The principal disadvantages of Stirling engines are:

(1) That a cooling system is required of approximately twice the capacity per horsepower compared with conventional internal combustion engines.

(2) To achieve high efficiencies and specific outputs, it is necessary to use helium or hydrogen as the working fluid at very high pressures (2,000 to 4,000 lb/in^2).

(3) The multiplicity of heat exchangers increases the cost to a value at least twice that of a diesel engine of corresponding power.

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Appendix B

AN ASSESSMENT OF THE STATE OF THE ART
OF STIRLING ENGINES FOR DoD APPLICATIONS

Extracted from a report prepared by:

Applied Concepts Corporation
Edinburg, VA

PREFACE

Appendix B is extracted from a report of research undertaken by Applied Concepts during January and February 1988. Its purpose was to establish the state of the art in Stirling engine developments aimed at six specified military applications, as part of a response to a request by the Office of the Secretary of Defense (OSD) for a study of Stirling cycle engine applications.

AN ASSESSMENT OF THE STATE OF THE ART OF STIRLING ENGINES FOR DoD APPLICATIONS

A. APPROACH

> Report on the state of the art in Stirling engine development
> aimed at the following applications:
>
> - Remotely piloted underwater vehicles
> - Mobile electric power
> - Auxiliary vehicle power
> - General purpose non-combat vehicles
> - Combat vehicles
> - Space vehicle power

Members of Applied Concepts' staff visited and conducted interviews at four of the five most experienced developers of Stirling engines in the United States. They held phone conversations with the fifth firm and also with a foreign engine developer. They visited the US Department of Energy (DOE) Heat Engine Propulsion Division, Office of Transportation Systems, and the National Aeronautics and Space Administration's Lewis Research Center (NASA LeRC), which has technical management responsibilities for four different Stirling engine development efforts being sponsored by US Government agencies. They visited the US Army's Belvoir Research Development and Engineering Center, which has supported Stirling engine development for mobile electric power since the late 1950s. They visited the US Army's Tank and Automotive Command (TACOM), which has responsibility for both combat and non-combat vehicle development, and they attended a project review where USAF Logistics Command (AFLC) personnel provided reports on their experience with two Stirling engine powered vehicles tested under DOE's Automotive Stirling Engine (ASE) program.
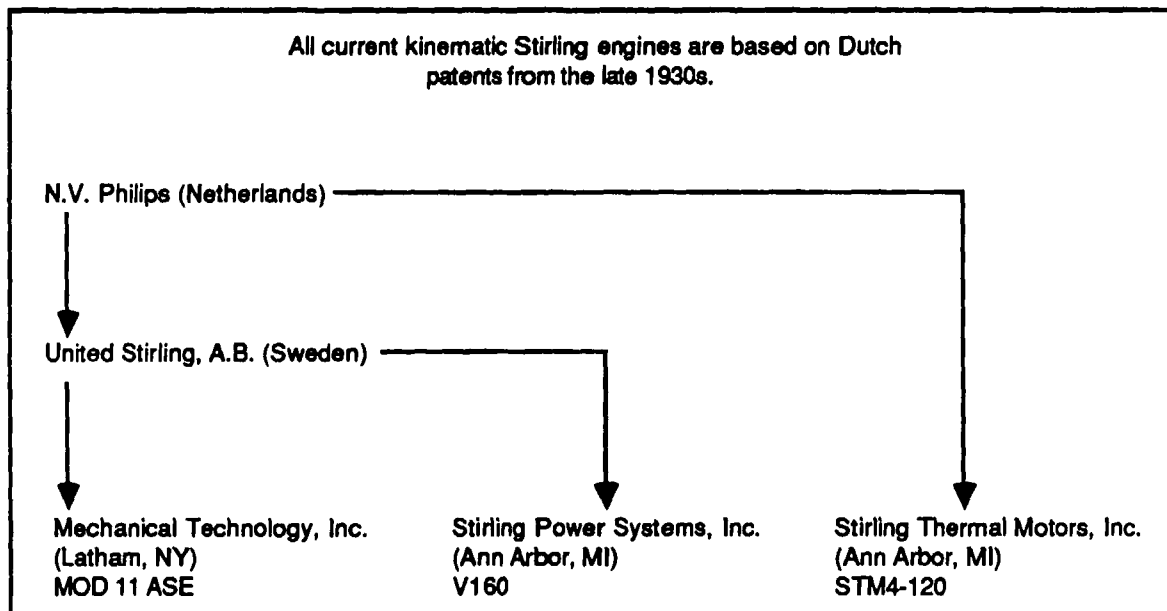
B. BACKGROUND

In this country since 1977 most of the funding for Stirling cycle engine development has come from the US Government, principally from the Department of Energy and, to a much lesser extent, the Department of Defense and the National Aeronautics and Space Administration. The Gas Research Institute has been a contributor to Stirling cycle engine research in the quest for an alternative engine which can utilize natural gas as a fuel. From time to time a number of corporations, including General Motors and Ford, have invested their own capital to fund research and development.

Any consideration of Stirling cycle engines must consider two different types of machines, referred to as kinematic Stirling engines (KSE) and free piston Stirling engines (FPSE). The thermodynamic cycle of the engines is the same and so are their major components (heater, regenerator, cooler, cylinder, and piston). Their configurations are quite different, however, as currently developed. Some of the design problems are correspondingly different. The state of the art is different, there being much more experience with kinematic engines than with free piston engines.

The second section looks in turn at specific military applications and whether the Stirling engine offers any advantages compared to its competition.

C. FIRMS CONDUCTING DEVELOPMENT OF KINEMATIC STIRLING ENGINES

All current kinematic Stirling engines are based on Dutch patents from the late 1930s.

N.V. Philips (Netherlands)

United Stirling, A.B. (Sweden)

Mechanical Technology, Inc.
(Latham, NY)
MOD 11 ASE

Stirling Power Systems, Inc.
(Ann Arbor, MI)
V160

Stirling Thermal Motors, Inc.
(Ann Arbor, MI)
STM4-120

NOTE: Both GMC and Ford held and abandoned licenses for KSE in the 1950s and 60s.

Current kinematic Stirling engine designs all share a line of development that can be traced to work done at N. V. Philips, the Dutch electronics corporation, between the late 1930s and 1950s. Engine development was carried out, under license, by General Motors during the 1960s and by Ford during the 1970s. During the late 1960s, United Stirling, A.B., of Sweden, became the principal license holder and developer, before being absorbed by Kochums Marine, A.B., in 1988.

The underlying factors contributing to KSE development have been the promise of potential benefits offered by the Stirling cycle versus the cost of developing an engine which could effectively realize those benefits.

The design problems have not been simple. A high efficiency Stirling engine depends on hydrogen as a working gas. A major problem has been sealing that gas in the engine, given that a shaft must penetrate the seal. Alternative working gases can be used, but the trade-off is reduced efficiency. The design of efficient and reliable combustors, heaters, coolers, and regenerators have also provided challenges.

Kinematic Stirling engines are known to be under development by three different US firms. These are Mechanical Technologies, Inc. (MTI), of Latham (Albany), New York; Stirling Power Systems Corporation (SPS) of Ann Arbor, Michigan; and Stirling Thermal Motors, Inc., (STM), also of Ann Arbor. The MTI and SPS engines are derived from United Stirling forerunners. The STM engine is derived from work done at Philips. The sum of their experience defines the state of the art for kinematic Stirling engine systems in the United States.

Engine systems are also known to be under development in several Western European countries, notably Sweden and France, and also by several companies in Japan. Component design and development and the fabrication of demonstrator engines are underway in a number of centers in the United States and abroad. As of January 1988, it is thought that the American firms are leaders in the state of the art, due largely to building upon European-developed technology during the 1970s and 1980s.

D. US KINEMATIC STIRLING ENGINE STATE OF THE ART

Firm	Model	Number Built	Operating Hours	Power (kW)	@RPM	Working Gas
MTI	Mod I	4	*	54	4,000	hydrogen
MTI	Mod I+	7	18,600	58	4,000	hydrogen
MTI	Mod II	2	800	60	4,000	hydrogen
STM	STM4-120	2	100	25	1,800	helium
SPS	V160	130	340,000	15	1,800	helium

* Included in Mod I+

Firm	Model	Number Pistons/ Volume per Piston (cc)	Hot Temp. (deg C)	Maximum Pressure (MPa)	Power Density (kG/kW)	Max. Thermal Efficiency	Mean Time Between Failures
MTI	Mod I	4•123	720	15	6.7	35%	15
MTI	Mod I+	4•125	820	15	6.1	37%	50
MTI	Mod II	4•120	820	15	3.7	40%	–
STM	STM4-120	4•120	812	13	6.7	45%	–
SPS	V160	1•160	720	15	6.7	28%	3,000

Note: All information is as provided by manufacturers.

The above figure provides a snapshot of the state of the art in kinematic Stirling cycle engines. Two US firms, Mechanical Technology, Inc., and Stirling Power Systems, have accumulated most experience with pre-production models of kinematic engines, including field testing of prototype systems. These firms are discussed in the following two sections.

Stirling Thermal Motors has carried out extensive component development and has accumulated limited experience with demonstrator engines. Their development program has focused on refinement of the swashplate drive, and on the use of liquid metal heat pipes for heat transfer from the combustor to the heater head.

E. AUTOMOTIVE STIRLING ENGINE

> **DOE has spent over $100 million on the ASE program leading to MOD II engine**
>
> **MOD I**
>
> - MTI has logged over 18,000 operating hours, including over 2,000 hours in vehicles
> - Engine availability, efficiency, and reliability has been significantly increased during program life
> - USAF has demonstrated operation on unleaded gasline, diesel fuel, and JP4
> - Hydrogen recharge rate is still on a 6-day schedule (target: 6 months)
> - MTBF improved from about 11 to about 50 hours
>
> **MOD II**
>
> - Lessons learned from MOD 1 engineered into MOD II
> - MOD II has a power density of 6 lbs per HP vs. 11 lbs/HP
> - Only one MOD II test vehicle funded (U.S. Postal Service van)
> - MTBF currently 90 hours
> - Deere/MTI agreement for 6.4 development seeking U.S. government cost sharing

The genesis of the automotive Stirling engine (ASE) program was the Arab oil embargo of 1973, which resulted in the late 1970s in the establishment of a Department of Energy (DOE) with an extensive research and development program aimed at exploiting alternative fuels. In later years, low emissions and fuel economy became more important programmatic goals. Automotive applications present serious technical challenges to Stirling engine development because the performance requirements necessitate a hydrogen working gas, while load-following requirements impose special problems for external combustion engines.

The market entry barriers to Stirling engine technology are high because a sophisticated and competitive major industry for automotive internal combustion engines already exists. The automotive industry had examined Stirling technologies in the decades prior to establishment of DOE, and found the expense of development unwarranted, given the satisfactory performance and existing infrastructure for other automotive engines.

Mechanical Technology, Inc., of Latham, New York, has been the prime contractor to DOE for the ASE program. This program took the United Stirling P-40 design as a basis for the MOD I engine, which was in turn enhanced to the MOD II. What has been accomplished, in summary, is the transfer of technology from Europe (i.e., United Stirling and, indirectly, Philips) to the United States, followed by a generational improvement (MOD I to MOD II) that is currently embodied in only two engines.

As indicated by the above figure, MTI accumulated extensive operating experience with the MOD I and MOD I enhanced engines, without ever fully solving component design problems. As might be expected, hydrogen leakage has remained a problem, although the recharge rate has been decreased from once a day to once every six days. Moreover, measurements on a MOD I+ engine indicated that leakage was due to heater head problems rather than to seals, and that recharge could be reduced by a further factor of 30 to twice a year. Mean time between failures was reduced to 50 hours, and overall automobile availability was increased from 36 percent to 92 percent. MOD II design is hoped to result in further significant improvements.

The Air Force has participated in field testing of the automotive Stirling engine (AFLC-MEEP). The Air Force demonstrated operation on three different fuels, including JP-4. MTI and Deere Corporation entered an agreement in February 1988 to conduct 6.4 level development. Also of interest is Deere's value engineering of the MOD II to effect a MOD II + design for producibility.

F. THE LOW-TECH, HIGH RELIABILITY APPROACH

- SPS has concentrated on developing a single design

- Has a lot in common with P-40 USAB technology

- Has achieved more production, more experience than any other manufacturer

- Claims over 340,000 hours experience and over 3,000 hours MTBF

- On subcontract to deliver 10 engines to Army to drive 5 kW generators

- Will provide "preproduction" engines for about $50,000, configured as generator sets

Stirling Power Systems (SPS), in contrast to MTI, has chosen to concentrate on bringing a single design to the point of commercialization. The V-160 was developed in Sweden by the FFV group, under license from United Stirling. SPS has set a goal of commercialization by 1991. The manufacturer claims significant progress has been made toward that goal, and pre-production engines are being offered for cogeneration and solar electric generator packages. SPS has used engine development contracts with the Army and with the Gas Research Institute, among others, as an important source of support.

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Most impressive is the manufacturer's claim to have produced over 130 engines with over 340,000 hours operating time. Mean time between failure is reported to have passed the 3,000-hour mark, two orders of magnitude improvement in recent years. The engine operates with helium as a working gas and achieves a 28 percent thermal conversion efficiency. The manufacturer indicates a 50 percent noise reduction over Otto cycle engines has been achieved, but this is only for the bare engine so does not include the noise of accessories.

Ten SPS V-160 driven generator sets were ordered by the Belvoir RD&E Center in 1984, subsequent to test of a prototype engine. Experience with the prototype indicated a short recharge cycle for the working gas (about 18 hours). Due to a dispute with the prime contractor, the generator sets, which were the result of a development contract, have yet to be delivered.

G. US FREE PISTON STIRLING ENGINE STATE OF THE ART

Firm	Model	# Built	Op Hrs.	Output Size (kWe)	@RPM	Working Gas
Sunpower	3kW	1	200	3.6	3,600	air
MTI	EM	3	5,000	3.3	3,600	helium
MTI	SPDE/RE	2	300	8.5	6,000	helium
STC	HP	15	>100,000	0.005*	3,000	helium
STC	RS	3	15	0.2*	3,000	helium

Firm	Model	Swept Vol. (cc)	Hot T (deg C)	Temp Ratio	Max P (MPa)	Power Density kG/kW	Max. Conversion Efficiency
Sunpower	3kW	870	750	3	2.4	30	18%
MTI	EM	204	760	3	6	50	25%
MTI	SPDE/RE	330	400	2	15	20	17%
STC	HP	0.4	300-700	2-3	21	–	20%
STC	RS	11.2	700	3	21	30	–

Note: All information is as provided by manufacturers

* Multiple Outputs

Free piston Stirling engines are known to be under development by three different US firms. Sunpower, Inc., of Athens, Ohio, and Mechanical Technology, Inc., of Latham, New York, have pursued designs based on patents by William Beale dating from

the early 1960s. These engines contain as few as two moving parts, and utilize gas bearings so that metallic surfaces do not contact one another. They typically incorporate a linear alternator driven by the power piston to induce an electric current in a coil external to the hermetically sealed engine. Components requiring special development efforts have included gas bearings and linear alternators, in addition to the heater head, regenerator, and cooler common to all Stirling engine designs. The free piston Stirling has the potential for very quiet operation, long life, low maintenance, and good efficiency.

Development of this engine concept has been variously sponsored, over the years, by the Department of Energy's Solar Thermal program, by the NASA/DoD SP100 program, and by the Army's Belvoir RD&E Center, among others. We estimate that a total of $10 to $15 million has been spent for all projects. Design details differ according to application, for example, space systems are optimized for radiator weight, leading to temperature ratios of only 2:1 instead of 3:1 for terrestrial applications. Nonetheless, there is a great deal of commonality, and progress in any one area represents progress in the state of the art.

Development can be characterized as being in the 6.2 to 6.3a stage. Experience with the most recent engines is only a few hundred hours, although NASA has run a 1-kW research engine for over 1,000 hours. The characterizing information provided in the figure should be interpreted as applying to demonstrator engines. All of the companies involved have advanced designs which incorporate lessons learned and which they, of course, hope will more closely meet performance targets.

A second development effort originated at McDonnell Douglas, continued at the University of Washington, and is currently embodied in Stirling Technology Company, with continuity of personnel. This effort has sought to develop a Stirling cycle heart pump since the 1960s, and has evolved through eight generations since that time. The current, and final, design is extremely compact and reliable. Prototypes have been tested for up to seven years of operation without a spontaneous system failure. As seen in the accompanying figure, this is a sealed, 5-watt system with helium as a working fluid. A unique and critical element of the design is the bellows which separates the working gas from the hydraulic fluid and transfers power to it. Development is in the 6.4 stage.

In recent years, STC has sought to realize other products based on free piston technology. Most significantly, during 1984-86 they built and delivered a 200-watt prototype engine to the Army's Natick RD&E Center. This engine was designed to

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provide "backpack" suit cooling for CBW protective suits. STC has designed a 25-kW engine for NASA Lewis and Sandia National Laboratories which is also, in essence, a scale-up of its heart pump. This system would convert the hydraulic wave into rotary kinetic energy to turn an alternator. Scale-up engines are in 6.2 to 6.3a stages of development.

MTI is currently pursuing, under sponsorship of the Gas Research Institute, a heat pump engine, which, like the STC concept, transfers power hydraulically to a compressor. The MTI design uses a metallic diaphragm as the transducer.

H. STIRLING ENGINE CHARACTERISTICS VERSUS MILITARY APPLICATIONS

		Applications					
Cited Potential Advantages:	ALREADY DEMON-STRATED?	UNDER WATER	MEP	APU	COMBAT VEH.	OTHER VEH.	SPACE
Low Noise/Vibration	Yes	●	○	●	○		●
Low Thermal Emission	Yes		○	●	●		
Fuel Choice	Yes	●	○	○		○	●
High Efficiency	No	○	○		●	○	●
Low Maintenance	No	○	○	○	○	○	●
Disadvantages:							
Cooling Requirements					≡	≡	
Power/Weight Ratio				≡	≡	≡	≡

● Critical need
○ Advantage
≡ Important liability

The above figure provides comparison between *potential* useful characteristics and selected DoD applications. Note that all of these characteristics would be useful from any engines. Stirlings have not demonstrated all of these characteristics, and, for those that have been demonstrated, the Stirling is not the only engine to have done so.

Low noise and vibration have been demonstrated in several engines, both kinematic and free piston. Measured values on the MOD II ASE engine increase from 95 dBa to 108 dBa over its range of engine speed. A comparable diesel engine is two to three times as loud. It should be noted, however, that the balance of system noise can increase noise emissions if not controlled and, of course, diesels can be sound insulated. Free piston designs probably have a higher potential for low noise and vibration than do KSE designs because they can be fully balanced engines.

Stirling cycle engines have been run on many different fuels. The ASE MOD I demonstration vehicles were operated on unleaded gasoline, diesel fuel, and JP4. The SPC heart pump is operated by heat stored by a eutectic salt, heated by electric resistance heating. NASA JPL has demonstrated engine operation from heat provided by point focusing solar collectors. Isotopic heat sources have been demonstrated by SPC. Many systems have used natural or bottled gas. A low technology air engine being demonstrated in Asia operates from burning rice husks.

High efficiency means fuel economy which means lower fuel load or extended range. This is a good feature for any application. It is critical for space applications, where fuel (or solar collectors) must be lifted into orbit. It is also critical for vehicles whose range is dependent on fuel load. Stirling engines have been demonstrated whose fuel economy rivals that of other engine designs. Achieved KSE efficiencies are higher than FPSE efficiencies. The latter can be expected to improve significantly if the linear alternator design is better developed.

Low maintenance requirements are highly desirable in any military application. In space, low maintenance or high mean time between failure is critical. In general, Stirlings have not yet demonstrated high reliability.

One of the major disadvantages of Stirling cycle engines is the need for increased cooling. In an internal combustion engine, roughly one-third of the heat is converted to usable energy, one-third is carried off as exhaust heat, and one-third is removed by coolant. For a Stirling engine, in which combustion occurs externally, there is no "exhaust," so the waste heat must all be removed by coolant, thus increasing the cooling system requirements by about 100 percent.

For underwater and maritime applications, the environment can provide the coolant. According to US Army TACOM, radiator requirements are prohibitive for packaging a Stirling cycle engine as a combat vehicle propulsion plant. For most other applications,

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radiator size is another cost to be considered in relation to benefits. This disadvantage is also reflected by the variable "power-to-weight ratio," which also includes other component characteristics such as the combustor.

I. MILITARY APPLICATIONS

1. Underwater Applications

- Principal advantage is low acoustic emissions

    --Detectability by threat forces
    --Interference with acoustic detection devices

- Ocean "heat sink" ameliorates cooling requirements

- Test rig demonstrators in Sweden (Kochums) and France (ECA)

- Kochums Marine, AB, has contract which allows for Stirling engines for Australian submarines

- U.S. Navy sees no need for Stirling to replace steam turbines when nuclear power is available

- For small submarine platforms, would like an available Stirling engine but unable/unwilling to justify a full engine development effort

- $250K contract to United Stirling for testing and data completed 1988

- Combustion gas exhaust no real problem

Unlike nations more concerned with *coastal* defense, the US Navy does not envision non-nuclear engines as potential candidates for propulsion of large, manned submarines. With nuclear power, the relative advantage of the Stirlings potentially high efficiency is reduced.

In the United States, as abroad, there is interest in quiet propulsion plants for small, unmanned underwater vehicles and the Stirling engine has demonstrated a capability for operation with a low acoustic signature. This can be important both for avoidance of detection and to minimize interference with friendly acoustical operations.

Stirling engines have long been considered candidates for underwater applications. The Stirling engine's capability to use stored heat, isotopic heat sources, or exotic isomolar combustion materials are an advantage, ʻʻthough according to the US Navy, technologies are readily available to handle the exhaust of standard combustion products.

United Stirling, A.B., has long been interested in underwater applications. Recently, the firm was absorbed into Kochums Marine, A.B., which will apparently be

devoting all of its remaining assets to the development of submarine propulsion plants. Kochums reportedly has a long-term contract with Australia to provide submarines. Part of that contract reportedly provides for the possible inclusion of Stirling engines as an auxiliary power plant. Both United Stirling, in Sweden, and Société ECA, in France, have demonstrated underwater propulsion plants in terrestrial test rigs.

The US Navy's David Taylor Research Laboratory considered sponsoring an engine development project for a small, underwater propulsion system but, given budget priorities, funded instead a smaller project to collect data from a United Stirling engine. No follow-on work is currently scheduled.

2. Mobile Electric Power

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• SLEEP ROC (1975) for quiet, lightweight, small electrical power plants

• Demonstrator engines delivered to FBRDC

    --1960s GMC 3kW? KSE
    --1982 MTI 3kW FPSE
    --1986 MTI 30kW KSE
    --1987 Sunpower 3kW air FPSE
    --1988? SPS 5kW KSE
    --1989? Sunpower 5kW helium FPSE
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DoD's most extensive involvement in Stirling engine development has been in this area. As early as the late 1950s, the predecessor to the Belvoir RD&E Center acquired Stirling engine driven generators from General Motors Corporation. In the early 1980s, Belvoir sponsored the development of a 3-kW FPSE driven generator set, but the technology was not yet mature enough for 6.3-level development, and it was impossible to complete program goals within the available budget.

In more recent years, Belvoir has tested a MOD I ASE configured as a 30-kW generator. This system was run for about 100 hours before problems were encountered in the control system and in hydrogen leakage. The Center sponsored the development of a 3-kW free piston demonstrator with air as the working gas. This project, although not completely successful, will probably lead to the design and test of a lighter, more efficient engine with helium as the working fluid. Around the same time, the Belvoir RD&E Center contracted for the development and delivery of 10 KSE driven 5-kW generators using the V-160 engine. Delayed by a contract dispute with the prime contractor, these sets may be delivered in 1988.

Part of the driver for Stirling cycle engine development for MEP applications is a May 1975 Required Operational Capability (ROC) for "a Family of Silent Lightweight Electric Energy Plants (SLEEP)." The requirement identifies a need for "a family of lightweight, compact, reliable, easily transported, electric energy plants that will be difficult to detect by visual, aural and IR means." The ROC contemplates development at the 6.4 level of research. It mandates that systems must equal or better the life cycle cost characteristics of the current generator family. Over the years, the Army has examined various technologies to meet these requirements without the funds to commit to a major engine development program, but with a substantial investment in test and demonstrator engines and other conversion devices.

Over the years, the requirement has become more clear and more generally applicable to a larger number of missions. As of this writing, Stirling cycle engines have demonstrated the noise and thermal emission characteristics envisioned by the ROC. Stirling engine driven generators have not yet demonstrated the reliability, availability, and maintainability necessary to achieve the program's cost objectives.

3. Auxiliary Power Units

- Potential advantages: Low accoustic signature, low thermal signature, run off available fuel.

- Potential to provide electric power in "hull down" status for tanks.

- No current DoD program.

Auxiliary power units are of interest to the Army and to the Navy for similar reasons. Idling the main propulsion engines of a ship or a combat vehicle in order to provide power for on-board systems (as opposed to propulsion) is an expensive proposition. Moreover, the noise and thermal emission signatures of main propulsion plants are typically much greater than any auxiliary power plant would produce. Army tactics for armored combat require that combat vehicles remain still and quiet in a passive mode, but ready for instant activation of certain on-board systems. Certain Naval applications require similar stealth. Both US Army TACOM and US Navy David Taylor Research Laboratory indicate a general need for and interest in vehicle-mounted APUs.

There are no current DoD programs to develop Stirling engines for APU. Their bulkiness is a critical disadvantage but APU requirements are similar to those of MEP applications in power so potential APU applications could benefit from any MEP research.

4. Non-Combat Vehicles

- Potential (modest) advantages same as general automotive Stirling engine applications.

- USAF participation in two demonstration vehicles.

- Multi-fuel (unleaded gasoline, diesel fuel, JP4) demonstrated by USAF.

In general, the same factors that apply to commercial automotive Stirling engines (ASE) also apply to non-combat vehicles for military use. DoD now uses commercial diesel engines for this application and use of Stirlings here will probably have to await their commercial development.

5. Combat Vehicles

- Potential Advantage: Low acoustic signatures, high efficiency.

- Critical Drawback: Low power density, cooling system requirements prohibit packaging in a combat vehicle.

Although certain Stirling engine characteristics are of abstract appeal for combat vehicle propulsion, the volume-to-power and weight-to-power ratios are too great to make it the engine of choice, even if fully developed. Auxiliary power units for combat vehicles and ships are discussed in subsection 3, above.

6. Space Power Systems

- **Advantages:** Higher efficiency means lighter load to orbit.

  Low vibration and good balance. Potential for low maintenance/long lifetime.

- A "primitive" terrestrial demonstrator

- Currently in 6.2 to 6.3a development at a low level of funding

Under a 1985 memorandum of agreement between the Strategic Defense Initiative Organization (DoD) and NASA's Office of Aeronautics and Space Technology, NASA Lewis Research Center has undertaken the development of technology leading to a space-qualified, high temperature, lightweight, Stirling engine for space power generation. MTI and Sunpower are the two principal contractors supporting this effort, which has achieved a terrestrial demonstration of a free piston space power demonstrator engine (SPDE). The SPDE was an inherently balanced, opposed-piston design, which has since been disassembled into two space power research engines (SPRE).

The SPDE was a rapid response, low-budget demonstrator. The SPDE/SPRE engines are the largest free piston engines ever built and operated. They achieved 87 percent of the design goal for engine power, and 68 percent for electrical power. The difference was due to losses in the linear alternator. Those losses have been modeled and are now thought to be understood, so improvements are expected in future designs.

Subsequent to the SPDE demonstration, NASA Lewis identified alternator efficiency, hydrodynamic bearings, and heat pipe heat exchangers as critical technology items. Component research is underway. New system designs have been completed, and proposals for design and fabrication of an experimental Stirling space engine (ESSE) and experimental endurance Stirling space engine are now in evaluation. The objective is full-scale engine tests by the end of 1992.

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