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Stirling Engine Application Study

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Prepared for
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Lewis Research Center
Under Contract DEN 3-254

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U.S. DEPARTMENT OF ENERGY
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16. Abstract
This report surveys a range of potential applications for Stirling engines in the power range from 0.5 to 5000 hp. Over one hundred such engine applications are grouped into a small number of classes (10), with the application in each class having a high degree of commonality in technical performance and cost requirements. A review of conventional engines (usually spark ignition or Diesel) was then undertaken to determine the degree to which commercial engine practice now serves the needs of the application classes and to determine the degree to which commercial engine practice now serves the needs of the application classes and to determine the nature of the competition faced by a new engine system. In each application class the Stirling engine was compared to the conventional engines, assuming that objectives of ongoing Stirling engine development programs are met. This ranking process indicated that Stirling engines showed potential for use in all application classes except very light duty applications (lawn mowers, etc.). However, this potential is contingent on demonstrating much greater operating life and reliability than has been demonstrated to date by developmental Stirling engine systems. This implies that future program initiatives in developing Stirling engine systems should give more emphasis to life and reliability issues than has been the case in ongoing programs.

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1.0 EXECUTIVE SUMMARY

SCOPE AND APPROACH

This report discusses the results of a program having as an overall objective, to assess the potential for Stirling engine applications in the 0.5-5000 hp output range.

The program was divided into two major task areas:

- o A Market Survey and Engine Requirements task during which the wide range of potential engine applications were organized into classes having similar technical and economic performance requirements.
- o A Stirling Engine Application Assessment task during which the potential for Stirling engines to serve the needs in each of the application classes identified in Task I was assessed.

The above activities required characterizing the performance levels of conventional (primarily spark ignition and Diesel internal combustion engines) engines used to serve different application categories and comparing these with both the present and projected characteristics of Stirling engines. The combination of information on application requirements and engine characteristics was then used to identify those classes of applications where Stirling engines may have some combination of advantages over alternative systems. Important technical requirements for Stirling engines to be successful in these applications were identified in order to help focus future R&D activities.

The above activities were undertaken by a combination of reviewing Stirling engine and conventional engine literature, discussions with organizations developing Stirling engines, and in-house analysis.

ENGINE APPLICATIONS

There are two general types of engine applications that were considered during

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the study. Those applications which are now served by commercially available engines, and those applications which are not now served by commercially available engines for any number of technical and economic reasons.

Total U.S. sales of conventional engines in 1978 was about 26 million units annually of which 25.6 million (98%) were gasoline, 0.62 million units (2%) were Diesel, and less than 3000 units were gas turbine or packaged Rankine cycle. Of these, over 92% had capacities below 150 hp and the total number sold annually above 2000 hp was less than 1000. The market for engines in the higher end of the study range is, therefore, very limited which reduces the incentive to commit R&D funds to serve this market segment.

Roughly half of all engines sold are small gasoline engines (under 10 hp) for light duty applications such as lawn mowers and chain saw drives.

Nearly all these low power applications are served by inexpensive, lightweight engines and it is doubtful that a Stirling engine could meet the needs of this large application class.

The primary market for engines over 10 hp is for automotive propulsion (45%), with the remaining market share divided among dozens of small market segments such as heavy duty vehicles, generator sets, and farm equipment. This study indicated that many of these applications might be served by Stirling engines if the performance goals of ongoing programs are achieved.

The Stirling engine appears to have a variety of favorable attributes applicable to a number of applications which, for one reason or another are not now served by conventional I.C. engines. Such applications include:

- Heat pump and total energy drives.
- Solar power.
- Thermal storage (underwater applications).
- Biomass fueled rural power.
- Space power (not within the scope of this study).

Even for the above applications, however, other power systems could be used. For example, modest improvements in the noise and emission levels of I.C. engines might make them suitable for commercial size gas fired heat pumps, while organic Rankine or Brayton cycle engines could be used in solar thermal applications.

It should also be noted that the market potential for all these non-conventional applications is highly uncertain and, as of now, there is no significant commercial experience on which to base market projections. For example, the market for gas fired heat pumps will depend more on the relative pricing of gas and electricity than on the technical merits of the drive systems.

In short, developing a Stirling engine for these unconventional applications involves a high degree of both technical and market risk.

APPLICATION RANKING

Over 100 applications for engines were identified during the literature review. Individual applications having similar technical performance requirements were grouped together into 10 application classes. The potential for the Stirling engine to compete on a technical and cost basis within each class was estimated using a numerical ranking system. Although the use of a numerical ranking system contributes to the objectivity of the ranking process, there is still a great deal of judgement exercised in assigning numerical scores to the various engine operating parameters.

The ranking process for Stirling engines at their present development status indicates that they are not competitive in any application class. This is due to the simple fact that Stirling engines have not demonstrated sufficient operating reliability or lifetimes to make them viable in any application of commercial interest.

Figure 1.1 shows the ranking of Stirling engines in 10 application classes, assuming success in ongoing development programs. The key assumptions made in

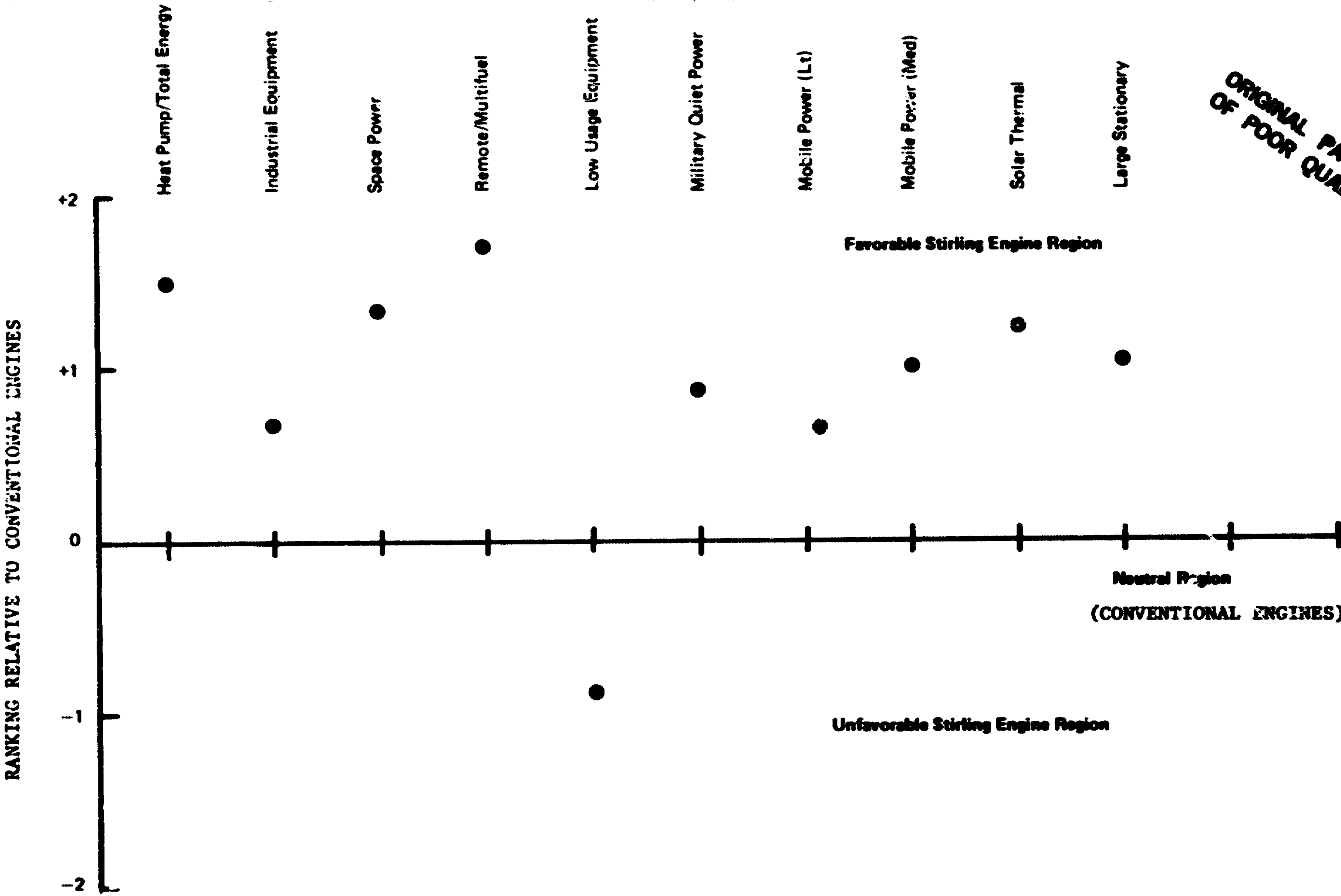

Figure 1.1 RELATIVE RANKING OF STIRLING ENGINE APPLICATIONS

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this ranking were that the reliability and life potential of the Stirling engine were achieved, while still maintaining good efficiency, noise, and emission characteristics. It was assumed that Stirling engines will be marginally larger and heavier, and somewhat more costly than their I.C. engine counterparts, due to basic configurational constraints.

The advantages of the Stirling engine over the conventional alternative are proportional to the distance above the neutral axis. There are several application classes including heat pumps/total energy, rural power, and silent generators which are particularly well addressed by Stirling engines due to a combination of their high efficiency, low noise levels, and multi-fuel capability.

The mass market, light duty cycle class of applications (lawn mowers, chain saws, etc.) has a negative rating due to the relatively large size and high cost of Stirling engines.

Vehicular propulsion applications are seen to have a rather modest positive ranking, reflecting in part, the success of the continuing development of current I.C. engine technology in addressing this class of application.

The advantages of vehicular Stirling engines include achieving even lower emission levels than now called for by Federal standards; a widely based, multi-fuel capability; and potentially better fuel mileage than delivered by current gasoline technology. Due to the critical factor that vehicular propulsion plays in national energy use and emissions, relatively modest improvements in performance levels can have significant overall impact on a national scale. As such, the development of an automotive Stirling engine would provide the country with additional flexibility in defining emission standards and fuel use strategies.

STIRLING ENGINE STATUS

The development of Stirling engines has been proceeding for over 40 years at organizations in Sweden, The Netherlands, and the United States. Most of the work on kinematic engines is based on technologies developed over the last 20 years at United Stirling (Sweden) and Philips (The Netherlands). Much of the activity in the United States in this field is based on a complex series of joint venture and license agreements with these foreign companies. As a practical matter, therefore, the number of participants in the Stirling engine field has been quite limited. This reflects, in part, the desire to maximize the use of the expertise contained in these organizations when initiating new programs, thereby increasing the probability of near-term success. However, this limited participation could inhibit the generation of new ideas and the introduction of new personnel into the field.

PERFORMANCE

Test bed Stirling engines have demonstrated many of their projected advantages, such as high efficiency (over 35% achieved), low emissions (well below EPA automotive limits), low noise, and multi-fuel operation. Configurations have been developed which can be placed under the hood of a mid-sized automobile and their weight can probably be consistent with most application requirements.

The primary development issues confronting Stirling engines now are similar to those which have historically been identified as problem areas: unproven reliability and life, and relatively high manufacturing costs.

Selected test engines have accumulated in excess of 5000 hours of operation. However, this operation has been accompanied by numerous unplanned shutdowns and replacement of key components. Typical operating periods are in the 50-100 hour range. As the result of the ongoing Stirling engine programs, significant progress has been made in improving the reliability of test engines and times between shutdown have been increasing on the automotive test engines.

Many of the reasons for unplanned system shutdown are related to instrumentation and auxiliary equipment failures which do not reflect directly on engine reliability per sé. However, several problem areas are basic to the Stirling engine configurations built to date and include:

- o Piston seals, which must operate unlubricated while still maintaining acceptable wear rates.

- o Reciprocating shaft seals which must both contain high pressure (2000+ psi) working gas and not allow oil into the working volume.
- o High temperature (1300°F+) heat transfer systems (heater head, air preheaters, combustion chamber) resulting in severe thermal stresses during cyclic operation.

While progress is being made in addressing these and other technical issues as a result of ongoing programs, one must still conclude that these currently are the major sources of design, life, and reliability difficulties.

COST

There is no commercial practice in Stirling engines to function as benchmark for cost projections and as a point of comparison with conventional engine alternatives. The Stirling engine does not require valves or a timed ignition system, which provides an outward appearance of simplicity when compared to a conventional I.C. engine. However, they require a complex, high temperature combustion/heat transfer subsystem, an enlarged radiator, and more complex auxiliary components and controls. The net result is that most observers project that the Stirling engine will have a cost which is 25-100% higher than for an I.C. engine of similar capacity and end use function. These observations are supported by preliminary studies done in support of the automotive program.

It should be noted, however, that a modest cost premium will be acceptable in a number of applications (heat pumps, total energy, etc.), if the Stirling engine has superior performance characteristics as compared to alternative systems.

KINEMATIC vs FREE PISTON CONFIGURATIONS

Most of the development efforts to date have been focussed on kinematic Stirling engines, whereby the engine output is rotary or shaft power. These configurations are necessary as a practical matter for vehicular applications and provide a great deal of flexibility since many forms of commercially available devices (compressors, pumps, etc.) can be connected to the output shaft. Kinematic engines require, however, the use of shaft seals to contain the high pressure working gas.

Free piston Stirling engines are a relatively recent development with major development activities starting in the early 1970's. They are conceptually simple and power can be extracted via linear alternators, hydraulic pumps, or gas compressors without the use of a shaft seal. As a result, the units can be hermetically sealed. The elimination of the shaft seal makes the free piston engine particularly interesting for low power applications where the mechanical losses of the seal can significantly impact engine efficiency. As a result of eliminating the need for shaft seals and being able to utilize gas gap or clearance piston seals, free piston Stirling engines show particularly good potential for achieving long life and high reliability. This is one reason why their use is being stressed for heat pump and space power applications where long life is very important. However, to date, free piston engines have not demonstrated their potential for superior reliability or life to kinematic engines. This, in part, reflects the relatively modest funding and a short period of time devoted to free piston engine developments. It is also due to the fact that free piston engines built to date have two of the problem areas which have been associated with kinematic engines - piston seals operating in an unlubricated area and high temperature heater head-combustor systems. However, the benefits of eliminating the shaft seal cannot be underestimated and it appears that the free piston system may be an attractive option, particularly in those applications where the power can be readily extracted from the engine, such as in heat pump, space power or natural gas liquifier systems.

STIRLING ENGINE REQUIREMENTS

In order to illustrate the technical and cost requirements for Stirling engine systems, preliminary specifications were prepared for four conceptual engine designs. The four designs were selected to cover a multiplicity of the favorable application classes identified by the ranking exercise so that the development risks could be spread among several potential markets. The engine designs selected were:

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- o A simple, multi-fuel engine for rural power applications.
- o A low noise power system for heat pump, electric generator and solar power applications.
- o A mid-size power system for vehicular drive, commercial total energy, and marine power applications.
- o A large, high efficiency, power system for co-generation and shipboard drives.

The low noise power system and mid-size power system engine designs were intended to address all favorable applications shown on Figure 1.1, except the Remote/Multifuel and Large Stationary classes. The simple, multifuel engine design is directed toward applications in the Remote/Multifuel class, and the large, high efficiency, power system design is meant to accommodate applications within the Large Stationary class.

The requirements for each engine design were estimated by comparison with performance of likely competitive systems and/or assessing the basic needs of the applications being served.

Table 1.1 summarizes the performance requirements used for conceptual design purposes. As indicated, the vehicular propulsion applications for the mid-size power plant place far more stringent requirements on low cost than for the engines serving other applications. For example, a biomass fired rural power unit could cost in excess of $500/kW and still be competitive with gasoline fired alternatives. On the other hand, all the non-automotive engines will require operational life in excess of 5,000 hours and for larger systems, in excess of 20,000 hours. Stirling engines can meet most of the operational requirements indicated in Table 1.1 based on demonstrated characteristics. However, the reliability and life requirements shown are far in excess of those demonstrated to date, and may pose a difficult challenge to future Stirling engine development programs.

FOREIGN MARKET

The study summarized in this report emphasizes domestic applications of

Table 1.1

PERFORMANCE REQUIREMENTS FOR SELECTED ENGINE DESIGNS

CHARACTERISTICS	RURAL POWER	SILENT POWER	AUTOMOTIVE POWER		AUTOMOTIVE-DERIVED POWER	LARGE STATIONARY POWER
Power Level	1-20 kW	3-30 kW	30-100 kW		30-100 kW	500-5000 kW
Efficiency	10-20%	25-30%	25-35%		30-40%	30-40%
Emissions	Not Important	Application Dependent	EPA Standards HC-.41, CO-3.4 NO_x-1.0 GM/Mile Particulates-.6 GM/Mile		Site Specific	To Meet Local Standards
Noise Level	Desirable but not essential	Low Noise Important (Less than 65-75 dBa @ 1 Meter)*	Low Noise Desirable (75-80 dBa @ 1M)		Site Specific	Application Dependent (No Federal Regulation at Present)
Heat Recovery	Not Important	Application Dependent	Of Minor Importance		Application Dependent	Application Dependent
Maintenance Interval	2-4 times/year (500-1000 hrs)	1-2 times/year (2000-5000 hrs)	LIGHT DUTY AUTO 250-500 hrs	HEAVY DUTY TRUCKS 1000-2000 hrs	2000-5000 hrs	4000-8000 hrs
Life Before Major Overhaul	7-10 years (5000-10000 hrs)	7-15 years 15000-25000 hrs)	2-3000 hrs	1000-2000 hrs	15000-25000 hrs	30000+ hrs
Cost	$200-400 for commercial fuels $400-600 for biomass fuels	$250-500/kW	$15-30/kW	$50-60/kW	$200-500/kW	$250-450/kW
Weight	30-60 kg/kW**	7-20 kg/kW	3-5 kg/kW	7-10 kg/kW	7-20 kg/kW	20-50 kg/kW
Size	.020-.080 M^3/kW	.003-.008 M^3/hr**	.003-.005 M^3/hr	.006-.009 M^3/kW	.005-.015 M^3/kW	.030-.100 M^3/kW

* Heat pump requirements used to quantify these parameters - some applications may have less severe demands.
** Based on a 50% allowance over available engines.

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Stirling engine systems. However, if Stirling engines are successfully developed they would have worldwide applicability and there are efforts underway in Japan and Europe to develop Stirling engines for a range of applications to serve their markets. In some cases, a combination of applications needs, government policies, and energy pricing could make the near-term use of Stirling engines more attractive in foreign applications than is now the case for domestic applications. Two such examples are illustrated in Appendix E. One is for the case of heat pump drives in Japan where government policies to even out large seasonal variations in electricity and gas use provide a strong incentive to accelerate the use of gas fired heat pump and total energy systems. Emphasis is being given to using Stirling engine drives in the residential and light commercial capacity ranges. The other example cited is the large potential in developing countries for small biomass fired Stirling engines to satisfy critical needs for irrigation, refrigeration, and village lighting, as an alternative to high operating cost Diesel generators or grid extensions. In both cases, it is quite likely that foreign manufacturers will rely heavily on the large U.S. based R&D programs in developing their systems. It is, therefore, important that both government and corporate strategies relative to the Stirling engine development and commercialization programs consider this export potential as well as the domestic markets.

DEVELOPMENT ISSUES

The previous sections indicate that a series of successfully developed Stirling engine systems would result in substantial differences in Stirling engine configurations and requirements and, hence, development needs.

A primary focus of both automotive and heat pump Stirling engine programs (which have received the bulk of R&D funding) has been to demonstrate that Stirling engines can meet the operational requirements of these two applications. As a result of these programs, Stirling engines have been successful in demonstrating their potential relative to such critical parameters as efficiency, emissions, multi-fuel capability, low noise operation, and acceptable size and weight (for automotive applications). Although further improvements in these areas is desirable, such improvements are probably not essential for commercial acceptance in many applications of widespread interest.

The critical issues which must be addressed by Stirling engine development programs relate to:

- Operational Life
- Reliability
- Cost

Successfully addressing these issues would result in an engine having overall advantages for some applications relative to conventional alternatives and being attractive for use in several applications which are not readily served by existing system options (high temperature solar, nuclear space, etc.).

Of the above issues, that pertaining to operational life is of major concern to all potential end users. Without acceptable life characteristics, all other engine attributes are of no significance at all. The lack of demonstrated, consistent operational reliability was also noted by several potential end users as their major reason for doubting the credibility of Stirling engines as a practical power system.

To some extent, it appears that the problems associated with attaining acceptable operational lifetimes has been related to the emphasis on developing a high performance automotive engine within a short period of time in order to address national policy goals. This emphasis has resulted in:

- Operating test engines at high speeds (4,000 rpm) required of a compact engine and emphasizing high heater head temperatures in order to achieve efficiencies consistent with high gas mileage.
- A relatively limited amount of long-term component development and testing in order to focus limited resources on developing and testing complete engine systems.
- An emphasis on R&D activities to support the goal of meeting the very stringent cost constraints imposed by automotive applications.

It should be noted that other Stirling engine programs (heat pumps) have also tended to emphasize achieving relatively stringent cost-performance goals rather than to demonstrate reliability and life. One of the primary challenges facing the Stirling engine community is, therefore, to demonstrate that Stirling engines can achieve respectable reliability and life goals using near-term modifications of these technologies that have been developed over the past 30 years. If the technology cannot be adapted to demonstrate reasonable life characteristics in the near-term, the resultant lack of credibility for the Stirling engine could result in erosion of both public and private sector support.

There is good reason to believe that more credible life and reliability characteristics can be achieved with Stirling engines using current technology. For example, reducing operating speeds may substantially increase the life of piston and shaft seals while reduced heater temperatures and lower heat fluxes could increase the reliability of heater heads. At the reduced performance levels, the engines may not be directly suitable for automotive or mass market heat pump applications. However, their performance may still be of interest for special markets which can be a starting point for wider use. This is, in fact, the strategy which appears to be followed by smaller companies using private sector funds.

Based on the above considerations (i.e., applicability of Stirling technology to a number of application categories) an integrated Stirling engine development program should give more emphasis to demonstrating life and reliability characteristics of widespread commercial interest. Such a program could include a combination of adapting existing technology to emphasize increased life and focussing more R&D resources on those critical issues now limiting life and reliability.

SUMMARY OF RESULTS

United States Market

A survey of engine applications within the United States was conducted during this study. Over one hundred engine applications were identified and grouped into the following ten classes, with each class having a high degree of commonality in technical performance and cost requirements:

- Heat Pump/Total Energy
- Industrial Equipment
- Space Power
- Remote/Multifuel
- Low Usage Equipment
- Military Quiet Power
- Mobile Power (Light)
- Mobile Power (Medium)
- Solar Thermal
- Large Stationary

Stirling and conventional engines were compared in each application class. the ranking process gave the following results.

- Stirling engines showed favorable potential for all applications except the Low Usage Equipment class (lawn mowers, etc.).
- Favorable Stirling engine application classes, which are currently served by conventional engines, represent a potential market of about 13 million engines per year.
- Stirling engines hold a distinct advantage over conventional engines as power sources in the Heat Pump/Total Energy, Space Power, Solar Thermal, and Remote/Multifuel application classes. There is, however, no present commercial practice on which to base market projections.

Four Stirling engine conceptual designs were defined that could address all of the nine favorable application classes.

- A simple, multifuel engine (1-20 kW).
- A low noise power system (3-30 kW).
- A mid-size power system for vehicle drives and stationary power (30-100 kW).
- A large, high efficiency power system (500-5000 kW).

Technology Needs

There remain some development needs that have not been adequately addressed by ongoing development programs. Achievement of the following goals are necessary in order to broaden the applicability of the Stirling engine.

- Demonstrate Stirling engine life, consistent with the needs of each application class, and show that maintenance requirements can be met.
- Consistently achieve a distinct efficiency advantage over the I.C. engine in order to provide an incentive for Stirling engine development.
- Emphasize Stirling engine designs - or modifications of engines of present development programs - which are consistent with long life, low maintenance operation. (Example: Stationary engine derived from automotive engine.)

If life and reliability goals can be demonstrated without a large compromise in efficiency, or increase in cost, the Stirling engine can be a highly competitive option for use in all nine favorable application classes.

Foreign Markets

Developing Countries

A biomass fired Stirling engine (Remote/Multifuel application class), using indigenous fuels, is an attractive power source alternative to Diesels and photovoltaic systems in developing countries. The value of this potential foreign Stirling engine market may total nearly 200 million dollars by 1990. This value corresponds to a power generating capability of 200 MW, or 40,000 5 kW engines.

Japan

Government policies relative to R&D funding, gas pricing, and tax incentives have been taken by the Japanese government to accelerate the introduction of gas fired systems - Stirling powered, and others. For this purpose, the

Government has initiated a 6 year, 40 million dollar program, in cooperation with industry and universities, to develop 3 and 30 kW sized engines to power the heat pump and total energy systems.

Pursuance of the above policies could create a relatively large Stirling engine market in Japan, and also put Japan in a very strong competitive position relative to the development of a similar market in the United States.

2.0 INTRODUCTION

2.1 Background

Stirling engines have been under development for over 40 years by organizations in Sweden, The Netherlands, and the United States. The interest level in the Stirling engine as a clean, efficient power converter has increased dramatically in the last 8-10 years as a result of rising world oil prices and concern for the environment. The total financial resources which have been devoted to Stirling engine development are estimated to be on the order of $500 million. This can be compared to the estimated engine R&D budget of a major United States automobile corporation of $600 million/year.* The resources directed toward Stirling engine development have, therefore, been relatively modest compared to those for automotive internal combustion engines.

Stirling engines have a number of potential advantages which have provided the incentive for these programs, including:

(a) Multifuel Capability which allows operation with a wide range of fossil fuels, as well as non-conventional heat inputs, such as solar energy, biomass, nuclear, and thermal storage.

(b) High Thermal Efficiency which results in more economic operation in those applications where fuel costs are important.

(c) Low Emission Levels in fuel fired applications as a result of being an external combustion engine. This advantage is particularly important in vehicular and in closed environment applications (mines, etc.).

(d) Low Noise and Vibration resulting from the use of mechanically balanced mechanisms, the lack of valves, relatively low operating speeds, and continuous combustion.

* Based on 4% of sales devoted to R&D and 25% of R&D going into engine systems.

(e) High Reliability and Long Life resulting from outwardly simple mechanical configurations and relatively few moving parts (no valves, etc.).

(f) Good Part Load and Variable Speed characteristics which are important for vehicular and some generator applications.

Many of the above advantages have been demonstrated in operating hardware. For example, efficiency levels in excess of 35 percent have been achieved as part of the automotive program and engines have been operated using solar, isotope, and thermal storage heat inputs. However, other attributes, such as high reliability, have not yet been demonstrated with the consistency required for commercial systems.

Despite its demonstrated and projected attributes, the stirling engine has still not found commercial acceptance. The reasons for this are complex and several of them are discussed briefly below.

- The primary funding for Stirling engine developments, particularly in the United States, has been for automotive applications. The low emission levels and high thermal efficiency (i.e., good gas mileage) potential of the Stirling engines make them well-suited for this application. However, the highly developed Internal Combustion (I.C.) engines now used, have themselves been the subject of continuing development effort over the last decade and are now, when combined with smaller cars, providing improved mileage and emission characteristics. These characteristics are achieved with engines having a selling price (\$25-30/kW) which probably cannot be achieved with a Stirling engine - even in mass production quantities. The projected performance characteristics of advanced automotive Stirling engines[1,2] indicated, however, that Stirling engines may have efficiency, fuel flexibility, and emission advantages over conventional I.C. engines. These advantages could become increasingly important in the future depending on cost and availability of clean automotive fuels. Thus, the goals behind the development of an automotive Stirling engine are a moving target.

- As a practical matter, conventional I.C. engines can address many of the applications considered for Stirling engines. I.C. engines have the benefit of over 50 years of extensive development and a firmly established sales/maintenance infrastructures throughout the world. As such, Stirling engines will require significant advantages over conventional engine options in order to result in a large market penetration.
- Current technology Stirling engines still have not demonstrated the life and reliability required to address the applications for which they are being considered. It is not certain that the technical reasons for the lack of demonstrated reliability can be successfully addressed for the mass market applications, while still maintaining the other required attributes (for example, high efficiency implies high operating temperatures which complicate achieving reliability and cost goals).
- Many engine systems indirectly utilize the production economies of the automotive and truck markets to maintain relatively low engine costs in a wide variety of applications. Examples of this include engine driven pumps, inboard marine engines, and standby engine/generators, which often use automotive or truck engine blocks as the basic building component. Stirling engines will be at a disadvantage in such applications if the automotive Stirling engine program is not pursued.
- Applications requiring unconventional heat inputs such as solar energy or isotopes can often be addressed by other external heat input engines. For example, several studies indicate that Stirling engines combined with high concentration ratio parabolic dish concentrators are an

attractive solar power option. However, there are several options being actively pursued for solar power including photovoltaics, solar driven Rankine engines, and solar driven Brayton engines. The early stage of development of these solar power technologies complicates the task of selecting the system with the best commercial potential and, therefore, the potential role of Stirling engines.

The above factors must be addressed when considering the prospects for Stirling engine commercialization efforts. In particular, the issues are:

- For what combination of applications do Stirling engines show significant advantages over probable competitive systems?
- What operating characteristics and cost goals must be achieved for Stirling engines to result in large penetrations into such markets?
- Do the sizes of potential markets for Stirling engines warrant Research and Development (R&D) effort to develop appropriate engine systems?
- What critical development needs must be addressed by ongoing Stirling engine development programs in order for the engines to show promise in making a meaningful penetration into these markets?

The program described herein has as an overall goal to address the above issues in order to assist the Department of Energy and NASA Lewis Research Center in determining which Stirling engine applications are most likely to be successful. In addition, this report identifies R&D initiatives needed to accelerate the introduction of Stirling engines in attractive application areas.

The results of this program will be one of the inputs used by program planners in DOE and NASA to direct future Stirling engine development programs and ensure that limited financial resources are utilized as effectively as possible.

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2.2 Purpose and Scope

The specific objectives of this study were to:

- o Assess the applicability of Stirling engines to a broad range of applications with capacity requirements of 0.5 to 5,000 hp.
- o Identify applications in which the operational advantages of Stirling engines could be particularly important and might, therefore, make them competitive with conventional engine systems.
- o Estimate the market potential for those classes of applications in which Stirling engines show promise of competitive performance.
- o Identify and comment on important technical, regulatory, and economic trends which might influence the potential market for Stirling engines.
- o Identify technology advancements required to result in competitive Stirling engine performance levels in those applications which appear to have the best promise.

This study emphasizes the application of Stirling engines in the United States. However, attention is drawn to foreign applications which might significantly expand the market for specific application classes.

The technical effort required to achieve the program objectives was divided into the following two tasks.

o Task I: Market Survey and Engine Requirements

Survey and organize engine applications by class (similar power level, duty cycle, etc.) and characterize the performance levels of conventional engines which are either now used or could be used in each application class.

o Task II: Stirling Engine Application Assessment

Assess the ability of a successfully developed Stirling engine to meet the requirements of each of the application classes identified in Task I and identify the technology advancements required to be competitive.

2.3 Program Approach

2.3.1 Task I

The overall approach to accomplish Task I is indicated in Figure 2.1 The primary activities which were undertaking during the Task I effort were:

Step 1: Survey of Engine Applications

A survey of engine applications was undertaken to identify both the range of possible engine applications and important requirements (efficiency, emissions, etc.) which must be satisfied by engines addressing the application. This activity included surveying both the Stirling engine literature and the literature pertaining to applications of conventional engine systems.

Step 2: Identification of Application Classes

Applications having similar technical and cost requirements were then grouped into classes which are now or could be served by common engine systems. Performance parameters that were considered in forming these application classes included efficiency, emissions, life, size, weight, part load operation, and noise level.

Step 3: Characterization of Conventional Engine Options

Conventional engine performance, and cost characteristics were reviewed and matched against the requirements of the application classes identified in Step 2. Conventional engine systems considered in this exercise included spark

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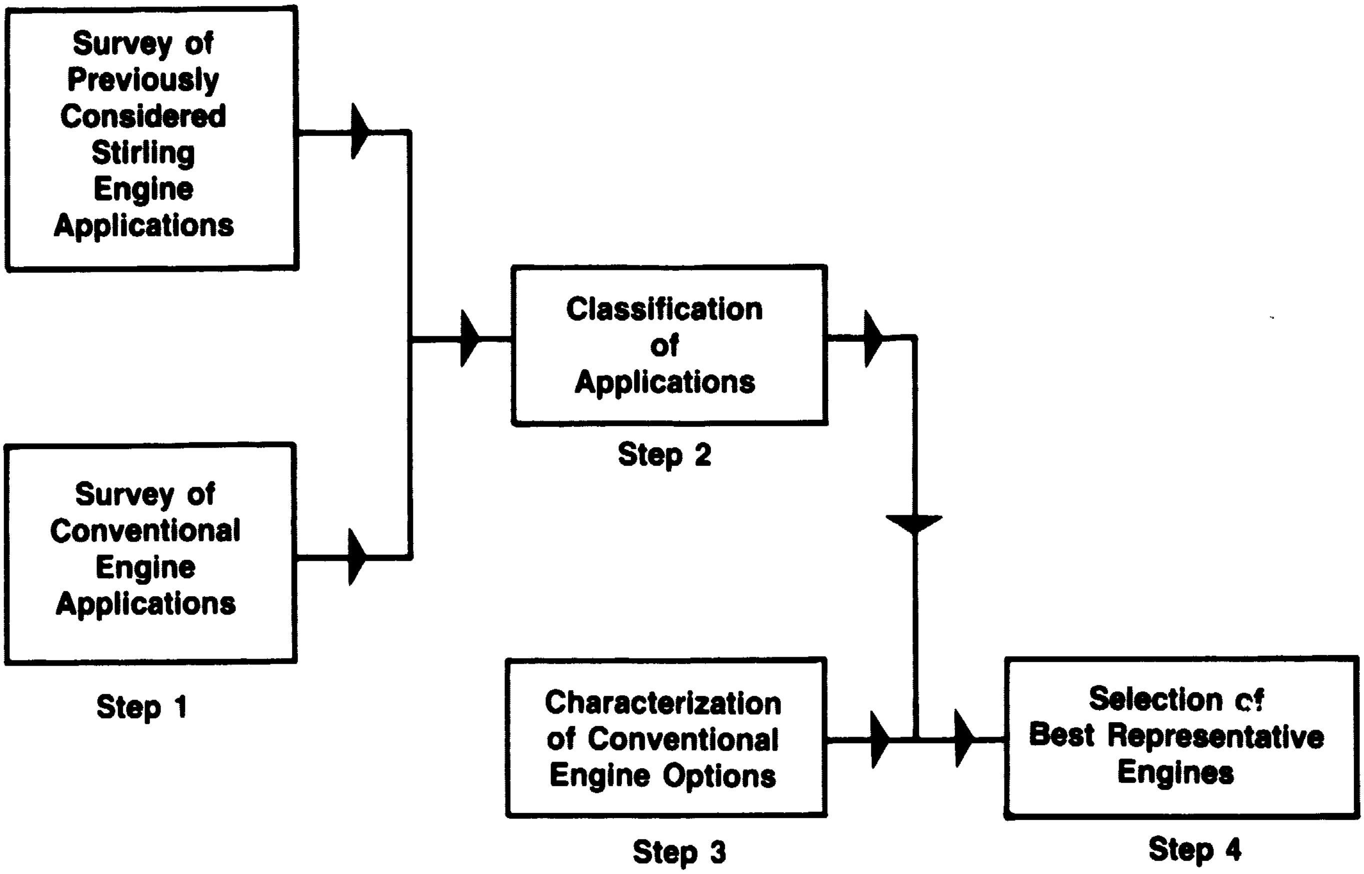

Figure 2.1 TASK I - "MARKET SURVEY" AND ENGINE REQUIREMENTS

ignition (gasoline) engines, diesel engines, small combustion turbines, and packaged Rankine cycle engines.

Step 4: Selection of Representative Engine

A representative engine which is either now or could be used to satisfy each of the application classes was selected and its performance characteristics summarized. The engine performance characteristics used tended to be for the better engines in each category so that the nature of the competition which must be addressed by Stirling engine developments was realistically assessed.

2.3.2 Task II

The overall approach to Task II is indicated in Figure 2.2. This task was divided into the following major steps.

Step 1: Stirling Engine Characteristics

The present status of Stirling engine technology was reviewed to quantify the operating characteristics of current developmental engines. also, qualitative judgements were made as to the probable operating characteristics of engines which might result from ongoing programs assuming a reasonable degree of success in current R&D programs.

Step 2: Stirling Engine/Application Class Ranking

The performance characteristics of developed Stirling engine systems were compared to those of likely competitive power systems (usually I.C. engines per Task I) for each of the application classes being considered. Numerical weights were attached to all important performance characteristics to assist in making the judgements required to quantitatively rank the suitability of Stirling engines to serve each application class.

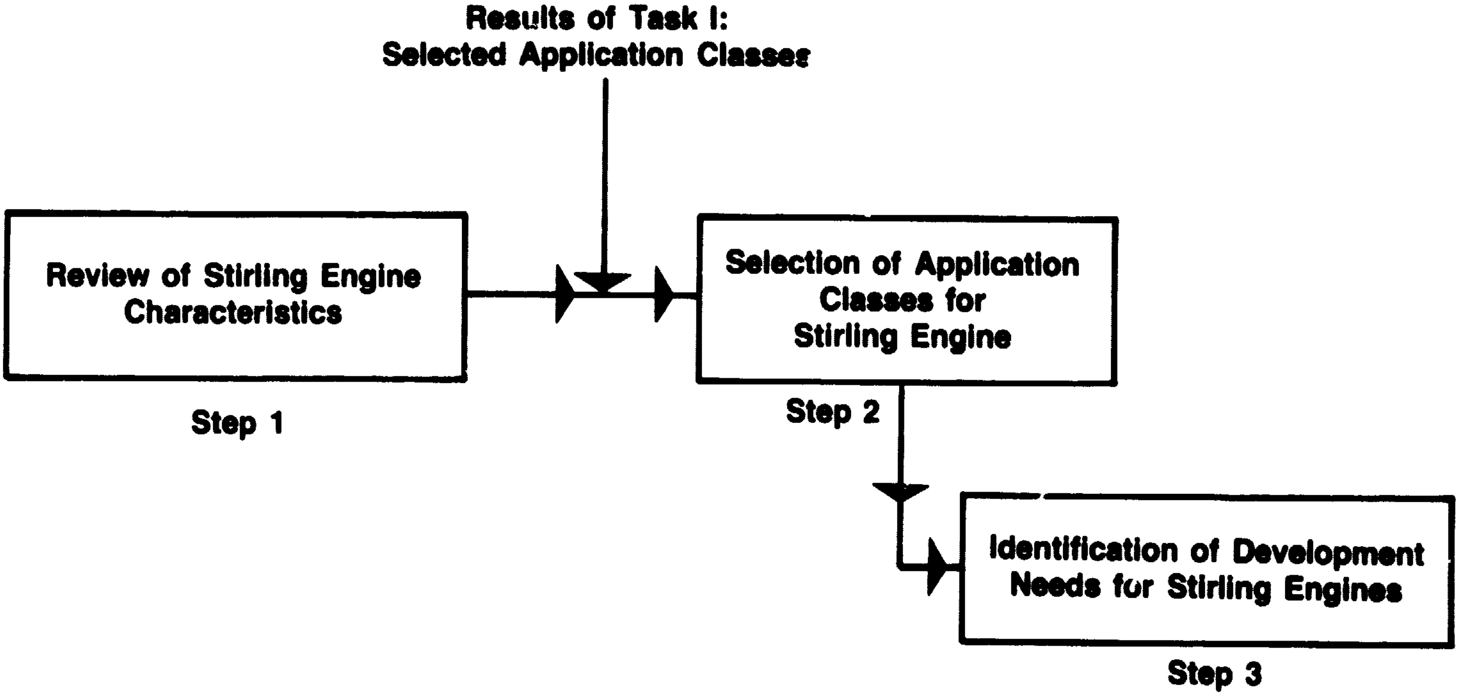

Figure 2.2 TASK II - STIRLING ENGINE APPLICATION ASSESSMENTS

Step 3: Stirling Engine Performance Requirements

The operational requirements and cost constraints for four Stirling engine systems which could serve a range of the favorable applications identified in Step 2 were quantified and conceptual designs were prepared for each of those engine classes indicating possible overall system configurations.

Step 4: Identification of System Development Needs

The required performance characteristics of Stirling engines defined in Step 3 were compared with those of present developmental Stirling engines and the goals of ongoing development programs. This comparison was used to help identify the nature of additional R&D activities which would help accelerate the use of Stirling engines in favorable applications.

3.0 SURVEY OF APPLICATIONS

A review of the technical and cost requirements of possible engine applications was undertaken in order to assist in the process of identifying those applications where the Stirling engine is most likely to be competitive. The results of this review were used in Section 4.0 to group applications into categories having common technical/cost requirements.

Over the last 20 years, extensive work has been done in the analyses of Stirling engines to serve a wide range of applications. In fact, Stirling engines have been considered for almost all major applications now served by conventional engines. In addition, Stirling engines have been considered for numerous applications which cannot be readily served by other available engines. Such applications include parabolic dish solar power systems, nuclear powered submarines, small scale biomass fired generators, and small space power systems. In order that this previous experience be factored into this program, a survey of the previous and present Stirling engine programs and application studies was conducted.

Also, in order to ensure that all potential applications of Stirling engines are considered, a survey of present engine practice was undertaken. In this way, present applictions for conventional engines were identified and quantified as to market size and engine characteristics. The results of this survey are discussed in detail in Section 5.0.

The approach taken in the survey of applications and a summary of its results follow.

3.1 Stirling Engine Applications

A review was made of Stirling engine applications which have been considered by the various groups working in this technology. The primary intent of this review was to determine:

- o Which applications have received the most attention.

- o Why Stirling engines were considered to be attractive for these applications.

This activity was undertaken by:

- o A review of the Stirling engine literature.
- o Interviews with experts in organizations which are now actively engaged in developing Stirling engines.

3.1.1 Literature Review

Over 200 papers and reports dealing with the application of Stirling engines were analyzed during the course of this review. These documents covered the important programs undertaken during the last 30 years, primarily in Europe, the United States, and Japan. A listing of these Stirling engine references is given in Appendix A.

The applications identified as part of this review process are summarized later in conjunction with other methods of survey. However, in general, the following observations can be made based on the results of this survey:

- o Over 25% of the literature deals with automotive applications of Stirling engines. This reflects the fact that most United States funding expended on Stirling engines over the last 20 years has been for such applications. The primary incentive behind pursuing this application for Stirling engines has been their potential for low exhaust emissions and good fuel mileage.
- o The other most common non-automotive applications considered for Stirling engines were gas fired heat pumps and solar thermal power units. The incentive for Stirling engines in heat pumps is their potential for low noise and vibration levels, high reliability, low emissions and good efficiency. The high efficiency of the Stirling engine is important in a solar application that uses a parabolic concentrator because an increase in conversion efficiency directly correlates to a reduction of concentrator size and cost.
- o Over 100 applications for Stirling engines were addressed in the literature. However, most of these applications were addressed primarily at the conceptual level so that only limited technical, cost, or market data was provided.

- With the exception of the automotive program reports, most of the literature emphasizes technical issues with relatively little discussion of economic, institutional, or market issues.
- Quantitative information provided on technical requirements of applications (especially reliability, noise levels, emission levels, etc.) was very limited in most instances.
- With the exception of the United States automotive program, there was only limited quantitative justification provided to support the selection of Stirling engines for the applications as compared to commercially available alternatives or with other developmental engine options (Brayton cycles, organic Rankine engines, fuel cells, adiabatic Diesel, etc.). Specifically, in few cases does the literature attempt to deal with the effect of improvements in conventional engine technology in assessing the potential for Stirling engines.

3.1.2 Interviews

Interviews were conducted with over 20 organizations active in the Stirling engine field. Organizations contacted include NASA Lewis Research Center, Department of Energy, Argonne National Laboratories, Mechanical Technologies, Inc., General Electric, Sunpower, Inc. (a participant in this study), and Philips. A complete list of contacts is provided in Appendix B, along with a list of current and past Stirling engine programs.

The purposes of the interviews were to:

- Discuss questions arising from the literature review.
- Obtain their latest views on potentially favorable applications and technology issues.

A general overview of the results of the interviews is given below. The interviews were conducted on an informal basis with minimal supporting documentation being provided. Therefore, the impressions indicated do not represent an industry concensus but rather provide insights into some of the issues being faced by the Stirling engine community.

- I.C. engines (Diesel, in particular) are very tough competition in most applications now served by conventional engines and the improvement

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in I.C. engine technology is creating a moving target for development of competitive Stirling engines.

- o The most commonly cited favorable application for Stirling engines was heat pumps - particularly in commercial sizes.
- o There appears to be a general feeling that Stirling engines might be a good option for using low-grade fuels (wood wastes, etc.).
- o One contact indicated that, to justify development of a Stirling engine, a multiplicity of suitable applications will have to be identified.
- o Several observers (particularly academic) emphasized the need for more imaginative R&D programs. However, little information was provided to indicate what R&D would be useful or why it would enhance Stirling engine prospects.

The interviews, in general, supported the results of the literature survey in identifying the most favorable applications. In particular, no new applications that were not extensively covered in the literature were identified during the course of the interviews.

Limited discussions were also held with a few organizations which have considered the use of Stirling engines in the past (military generators, submarine propulsion, vehicular propulsion), to solicit their views on future prospects. The primary impression resulting from these discussions was a general concern over the life and reliability history of the Stirling engine, with both past and present operating experience cited to support this view.

This issue appears to be important to many of the potential users of Stirling engine systems in both civilian and military applications and must be successfully addressed to increase the level of interest in Stirling engine systems.

3.2 Conventional Engine Applications

Most potential applications of Stirling engines are already being addressed by one or more conventional engines. In this context, conventional engines include spark ignition (gasoline or gaseous fuel), compression ignition (Diesel or dual fuel), gas turbine, and small Rankine engines. In order to determine the requirements of existing engine applications, their characteristics were reviewed using, in large part, Arthur D. Little's existing in-house data base. For this study, the Arthur D. Little data base was supplemented with a literature search and the use of a market study entitled Engine Data V published by Power Systems Research, Inc. (Appendix A).

3.2.1 In-House Data Review

The in-house data review consisted of two distinctly separate efforts.

- o Extraction of relevant data from Arthur D. Little's data base.
- o Discussions with Arthur D. Little staff with extensive experience in various fields in which engines are utilized.

The Arthur D. Little data base contains information on engine applications in the areas of:

- o Industrial equipment,
- o Marine (pleasure craft and light commercial).
- o Agricultural equipment.
- o Lawn and garden equipment.
- o Compressors (portable).
- o Passenger cars.
- o Trucks (light, medium, and heavy duty).
- o Welders.
- o Construction equipment.
- o Generator sets.
- o Mobile refrigeration equipment.
- o Light and experimental aircraft.
- o Natural gas pipeline engine applications.
- o Heat pumps.

Specific data were compiled for each engine application, the categories for which are listed as follows:

- o Power and torque vs speed.
- o Engine weight.
- o Durability and reliability.
- o Serviceability and maintainability.

- Fuel consumption.
- Emissions.
- Life (and time between overhauls).
- Size.
- Initial cost, overhead costs.
- Multiple fuel capability/adaptability.
- Number of cylinders.
- Engine configuration (in-line, vee, opposed, etc.).
- Liquid vs air cooling.
- Bell housing and flywheel options.

Much of the in-house data was obtained through person-to-person and/or telephone interviews of engine or equipment manufacturers in North America, Europe, and Japan.

In performing this work, great care was taken to insure that the needs of an application were separated from the actual characteristics of engines presently serving that need. This is because in a majority of applications, the operating characteristics of the equipment driven by those engines were designed around specific engine performance requirements or capabilities (speed range, duty cycles, etc.). Subsequently, engine manufacturers designed new engines to fit into the existing operating requirements. This is done in order to maximize the interchangeability of one's engines with those of a competitive make. Only when a manufacturer has control over both the engine and its equipment application, as in automotive use, for example, are the performance characteristics of engines optimized to fulfill the needs of a particular end use.

By separating the desired engine characteristics from the current engine characteristics, the influence of existing engines over application requirements can be removed where appropriate. Once this is done, the Stirling engine can be judged (in Task 2) against the actual needs of an application in terms of engine features, instead of competing against attributes of present engines which may or may not be necessary for any given application.

The existing data base and the experiences of the staff who compiled it was expanded through a series of interviews with Arthur D. Little staff who specialize in selected areas where engines are used. This effort covered both conventional and non-conventional applications of shaft power in the fields of Mining, Agriculture, and Heavy Industry. Those applications which tend to utilize one or more potential Stirling engine attributes were sought out. Special attention was give to I.C. engine driven applications where Stirling engines are likely to have some potential. In general, mining and agricultural applications appear quite limited due to relatively low market volumes.

3.3 Results of Surveys and Classification of Applications

The information obtained during the survey of Stirling and conventional engine applications identified over 100 possible applications where engines are either now in use or could be used if engines with the right characteristics were available. These applications are listed in Table 3.1. The operational advantages expected from Stirling engines in these applications are also indicated. Specific operational advantages which are noted are:

- The need for a Multi Fuel Capability, in order to be able to use non-distillate fuels such as heavy oils, biomass, coal, solar energy, isotopes, or thermal storage.
- Low Emissions, in order to satisfy environmental regulations or consumer requirements.
- High Efficiency levels in order to reduce operating costs or, in some cases, such as in solar thermal systems reduce overall system costs.
- Low Noise and Vibration, which can be particularly important in applications such as residential heat pumps, and pleasure boats.
- Low Maintenance, which is very important for remote applications or high duty cycle applications.
- Heat Recovery, which is necessary in the operation of heat pump and total energy systems.

It should be emphasized that attributing one of the above characteristics to a specific application is often highly judgemental and doing so is intended primarily to guide the effort of future tasks in identifying applications which might have common engine requirements.

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TABLE 3.1

POTENTIAL ENGINE APPLICATIONS AND SELECTED OPERATIONAL ADVANTAGES

X: Denotes a requirement

APPLICATIONS	MULTIFUEL CAPABILITY	LOW EMISSIONS	HIGH EFFICIENCY	LOW NOISE	LOW VIBRATION	LOW MAINTENANCE	HEAT RECOVERY
1. ELECTRIC POWER GENERATION							
Quiet Electric Power Generation for Army	X			X	X	X	
Quiet Electric Power Generation for Recreation Vehicles, Mobile Homes, etc.	X	X	X	X	X		X
Remote Electric Power using Solar/Biomass Liquid Fuels	X		X			X	
Central Power Station/Stationary Application	X	X	X			X	X
Reliable Electric Power For Telephone Switching Station		X	X	X	X	X	
Isotope Powered Electric Generator			X	X	X	X	
Lighthouse Applications	X		X			X	
Short Duration Underwater Power Plant			X	X	X	X	X
Municipal Power Generation using Municipal & Agricultural Wastes	X	X	X			X	X
Power Generation from Coal-Derived Fuels, Low Grade Petroleum, etc.	X	X	X			X	
Signal Buoys, Sonobuoys			X		X	X	
Communications Booster Stations			X			X	
Emergency and Standby Electric Power (hospital, industry)		X		X	X	X	
Portable Generators		X	X	X	X	X	
Peaking Generators		X	X			X	
Off-Shore Oil Platform			X	X	X	X	X

Arthur D. Little, Inc.

TABLE 3.1 (Continued)

X: Denotes a requirement APPLICATIONS	MULTIFUEL CAPABILITY	LOW EMISSIONS	HIGH EFFICIENCY	LOW NOISE	LOW VIBRATION	LOW MAINTENANCE	HEAT RECOVERY
2. HEAT PUMP APPLICATIONS							
Heat Pump Drive for Residential/ Commercial Application	X	X	X	X	X	X	X
Industrial Heat Pumps	X	X	X			X	X
Advanced Heat Pump Applications (using cycles such as Stirling-Stirling)		X	X			X	X
3. MEDICAL APPLICATIONS							
Powered Wheelchair	X	X	X	X	X		
Portable Refrigerator for Storing Biological Samples/Blood, etc.		X	X	X	X	X	
4. REMOTE/THIRD WORLD APPLICATIONS							
Ventilating Fans in Remote Areas	X	X	X	X	X		
Cold Storage of Food in Remote Areas	X		X	X		X	
TV/Radio in Remote Areas Fuel: Wood, Hay, Rice Husk, Charcoal, etc.	X	X	X	X			
Wood Splitter/Cordwood Saws using wood fuel	X	X	X				
Portable Refrigerators for Recreation Vehicles/Yachts	X	X	X	X	X	X	X
Rural Well-Water Pumps	X		X	X		X	
Rural Irrigation Pumps	X		X			X	
Back-Pack Power Plant		X	X	X	X		

TABLE 3.1 (Continued)

X: Denotes a requirement APPLICATIONS	MULTIFUEL CAPABILITY	LOW EMISSIONS	HIGH EFFICIENCY	LOW NOISE	LOW VIBRATION	LOW MAINTENANCE	HEAT RECOVERY
Remote Meteorological Stations			X			X	
Microwave Relay Station			X			X	
5. AGRICULTURE							
Tractors	X		X			X	
Farm Equipment (self-powered)	X		X			X	
Logging Machines	X		X			X	
Grain Drying	X		X			X	X
Rototillers	X		X				
Forestry	X		X				
6. MINING							
Shuttle Cars for Underground Mines	X	X	X	X	X	X	
Power Generation in Mines	X	X	X	X	X	X	X
Surface Mining	X		X	X		X	
Auxiliary Vehicles Inside Mines	X	X	X	X	X	X	
7. TRANSPORTATION							
Passenger Cars	X	X	X	X	X	X	
Trucks	X	X	X	X		X	
Bus	X	X	X	X	X	X	
Road Cleaning	X		X	X			

TABLE 3.1 (Continued)

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X: Denotes a requirement

APPLICATIONS	MULTIFUEL CAPABILITY	LOW EMISSIONS	HIGH EFFICIENCY	LOW NOISE	LOW VIBRATION	LOW MAINTENANCE	HEAT RECOVERY
Taxi	X	X	X	X	X	X	
Rail Applications, using coal or conventional fuels (elect. or hydraulic)	X	X	X			X	
Rail Maintenance Equipment	X		X			X	
Motorcycles		X	X	X	X		
Mopeds		X	X	X	X		
Delivery Trucks	X	X	X	X		X	
Hybrid Electric Vehicles	X	X	X	X	X	X	
Small Cars for Shoppers	X	X	X	X	X		
8. CONSTRUCTION							
Quiet Air Compressor		X	X	X		X	
Tractors			X			X	
Scraper Shovel			X			X	
Saw			X			X	
Roller			X		X	X	
Pile Drive			X			X	
Front End Loader			X			X	
Paving Breaker			X			X	
Grader			X		X	X	
Mobile Crane			X			X	
Derrick Crane			X			X	
Concrete Pump			X			X	
Concrete Mixer			X			X	
Contractor Pumps			X			X	

TABLE 3.1 (Continued)

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APPLICATIONS	MULTIFUEL CAPABILITY	LOW EMISSIONS	HIGH EFFICIENCY	LOW NOISE	LOW VIBRATION	LOW MAINTENANCE	HEAT RECOVERY
9. INDUSTRIAL APPLICATIONS							
Compressors (Portable and Stationary)		X	X				
Indoor Equipment - Forklift Trucks, etc.		X	X	X	X	X	
Welders		X	X			X	
Mobile Refrigeration Equipment		X	X	X	X	X	
Undersea Mining	X		X	X	X	X	
Submersibles or Crawlers for off-shore Oil and Gas Industry	X		X	X	X	X	X
Gas Compression/Liquefaction	X		X			X	
Industrial Trucks (Light, Medium and Heavy)	X	X	X			X	
Industrial Drives	X		X				
Natural Gas Pipeline Applications (Compressor)			X			X	
Gas Gathering	X		X			X	
Industrial Equipment - Outdoors	X		X			X	
Hydraulic Drive in enclosed spaces	X	X	X	X	X		
10. Industrial Cogeneration	X		X			X	
High Temperature Waste Heat Source for Power Generation	X		X				
Residential/Commercial **Total Energy** Power/Heat Source for Pleasure Boats	X	X	X	X	X	X	X
11. MILITARY APPLICATIONS							
Compressor (Portable and Stationary)	X			X		X	
Submarien/Underwater/Gen. Purpose	X		X	X	X	X	X

TABLE 3.1 (Continued)

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APPLICATIONS	MULTIFUEL CAPABILITY	LOW EMISSIONS	HIGH EFFICIENCY	LOW NOISE	LOW VIBRATION	LOW MAINTENANCE	HEAT RECOVERY
Marine Generators for Navy	X					X	
Marien Prime Movers for Navy	X					X	
Small Research Submarines			X	X	X	X	X
Large Military Submarines	X		X	X	X	X	X
Unattended Surveillance Devices			X	X	X	X	
Nuclear or Solar power generation for command posts	X		X	X	X	X	
Military Vehicles (Trucks)	X			X	X	X	
Military Control and Logistical Vehicles	X			X	X	X	
Military Naval Vessels	X		X			X	
Military Tanks	X			X		X	
12. RESIDENTIAL APPLICATIONS/CONSUMER PRODUCTS							
Lawn and Garden				X			
Snow Blower				X			
Chain Saw				X			
Power Tools				X			
Compressor for Consumers				X			
13. SOLAR THERMAL APPLICATIONS							
Solar Thermal Power (Dish Mounted)			X	X	X	X	
Solar Powered Pumps			X	X			
Solar Powered Compressors for shop air, etc.			X	X		X	

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TABLE 3.1 (Continued)

X: Denotes a requirement

APPLICATIONS	MULTIFUEL CAPABILITY	LOW EMISSIONS	HIGH EFFICIENCY	LOW NOISE	LOW VIBRATION	LOW MAINTENANCE	HEAT RECOVERY
14. COOLING							
Cryogenic Cooling			X			X	
Residential/Commercial Air Conditioner		X	X	X	X	X	
15. SPACE APPLICATIONS							
Radio-Isotope Powered Space Application			X	X	X	X	
Solar Powered Space Power System			X	X	X	X	
16. MARINE APPLICATIONS (Commercial)							
Ocean Vessels	X		X		X	X	
Commercial Coastal Vessels	X		X		X	X	
Commercial Offshore Vessels	X		X		X	X	
Commercial Inland Waterways Vessels	X		X		X	X	

For the development of Table 3.1, the applications have been listed under titles descriptive of their end use. This division is quite arbitrary and was selected primarily because available information sources tend to group engine applications into similar categories. It should be emphasized, however, that there is often a wide range of engine requirements within any of the above application categories. For example, electric power generators range from 3 hp standby generators to 5,000 hp continuous duty cycle generators for off-shore oil platforms. Similarly, transportation applications include fractional hp moped engines as well as high duty cycle 500 hp truck engines. As such, the end use categories are, in some cases, not particularly useful in identifying applications which have common engine requirements.

4.0 CLASSIFICATION OF APPLICATIONS

In addition to some duplicate descriptions under different categories, many of the applications in Table 3.1 have similar cost, performance, and capacity requirements. For example, the engine requirements for a residential heat pump and a military generator are similar in almost all respects even though the end use functions differ greatly. Similarly such diverse conventional applications as an engine driven water pump for irrigation (in the United States Southwest) and automobiles have similar capacity and cost constraints, which often results in their being served by common engines. As a result, most conventional engines are used to satisfy a number of diverse applications with attendant development and production economies.

The grouping of such a large number of overlapping and divergent applications into a small number of classes is a highly judgemental process. After elimination of duplicates and obviously similar applications, a computer based "Cluster Analysis" technique was utilized in order to assist in the grouping process. This technique required assigning numerical weighting to the various application requirements and then logically grouping applications so as to maximize common desired characteristics. This Cluster analysis is described in Appendix D along with the input data used to numerically catagorize the individual applications.

As a result of both the Cluster Analysis and informed judgements, the sixteen classes of applications identified in Section 3.0 were reorganized into ten categories having common requirements.

Information provided for each class of applications includes:

- o The power requirements of engines commonly utilized for applications which are now served by conventional engines or which are likely to be needed for applications not now served by any engine type.
- o Estimated aggregate market size. For applications now served by conventional I.C. engines, the market indicated is the actual sales of engines usually used in the application class under consideration (discussed in more detail in Section 5.0). The term NCP (no commercial

practice) is used where there is no significant commercial use of any conventional engine on which to base market size.

- The important operational characteristics required of each application class. Many of these are quantified during the discussion of conventional engine characteristics (Section 5.0) and the selection of application classes showing particular promise for Stirling engines (Section 7.0).

Several of the important characteristics of each application class identified in Table 4.1 are outlined briefly below.

A. Heat Pump and Total Energy

In a heat pump/total energy application, an engine would need low emissions, good fuel efficiency, very low noise and vibration, heat recovery, infrequent maintenance, long life, and good startability. Not so critical to engine success in this application are low engine cost and weight, small engine size and good load following.

B. Industrial Equipment

Fuel switching capability, low noise and vibration, heat recovery, low weight and small engine size are not critical in industrial equipment. However, low emissions, good fuel efficiency, long life, good startability, low cost and good load following are important in these applications.

C. Nuclear Power (Space)

In a nuclear (isotope or reactor) space power system, fuel efficiency, low noise and vibration, long life, startability and load following are critical parameters. Fuel switching, low emissions, heat recovery and low engine cost are not important in these applications.

D. Long-Run, Remote, Multi-Fuel Applications

In a rural power system, fuel switching, fuel efficiency, low maintenance, long life and startability are important characteristics. Low emissions, low noise and vibration, heat recovery and engine size and weight are not critical.

E. Low Usage Equipment

In low usage equipment the main factor for success are very low cost, startability, low engine weight and small size. Other factors are not critical such as efficiency or heat recovery.

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Table 4.1

SUMMARY OF APPLICATION CLASS GROUPING

	Application Class	Power Range	1980 Market Size (Annual)	Qualitative Requirements
A.	Heat Pump & Total Energy			
	Residential Heat Pump	2-10 kW	– Limited practice to date	– Long life
	Commercial Heat Pump	30-60 kW	– Large potential if technical	– High efficiency
	Industrial Heat Pump	100-200 kW	and cost goals achieved	– Low noise & vibration
				– Low emissions
				– Heat recovery
				– Very high reliability
				– Low maintenance
B.	Industrial Equipment			
	Industrial Indoor Eq. (Forklifts-Gas)	15-175 kW	55,600	– High efficiency
	Industrial Outdoor Eq.	5-525 kW	61,400	– Long life
	Compressors for Construction	20-500 kW	26,100	– Low emissions
	Isolated Power Generation	6-475 kW }	381,600	– Average cost
	Misc. Generation	1-560 kW }		– Good load following
	Agricultural Irrigation	3-300 kW	27,900	– High reliability
	Fire Pumps	60-450 kW	7,400	
C.	Isotope or Reactor Powered			
	Ground Power Units	20-100 kW	– NCP**	– Very high reliability
	Spaceborne Power Units	$1\text{-}1000^{+}$ kW	– Significant potential for space	– Long life
			applications as space power	– High efficiency
			needs increase	– Low weight (space applications)
				– Low noise and vibration
				– Good load following

Table 4.1 (Continued)

Application Class	Power Range	1980 Market Size (Annual)	Qualitative Requirements
D. Long-Run, Remote, Potentially Multi-Fuel Applications			
Ventilating Fans			– Low maintenance
Portable Refrigeration			– Long life
Mobile Refrigeration	8-50 kW	21,500	– High efficiency
Gas Gathering	25-450 kW	Small	– Multi-fuel use
Third World or Remote Power Generation	8-150 kW	– Large potential for biomass fired systems	– Simple construction & maintenance – High reliability
Oil Pumping	8-200 kW	Small	
E. Low Usage Equipment			
E.1. Low Power			
Compressors (Consumer) (Gas)	3-12 kW	10,300	– Low cost
Generators (Portable) (Gas)	1-10 kW	205,200	– Compact
Generators (Rec. Veh)	1-10 kW		– Simple operation
Consumer Goods (Lawn & Garden)	2-20 kW	9,926,000	– Lightweight
Pumps (General Purpose)	1-12 kW	77,400	– High reliability
Log Splitters	2-8 kW	144,600	
Chain Saws		2,473,600	
Snowmobiles		101,500	
E.2. High Power			
Welders	8-175 kW	96,000	
Pumps-Contractor	12-425 kW	33,800	
Generators (Emergency)	11-560 kW	169,700	
E.3. Back Pack Power Supply	1-4 kW		
F. Military			
Portable Electric Generators	< 15 kW > 15 kW	No longer produced 400-600*	– Fuel switching – Low noise & vibration – High efficiency – Good load following – High reliability – Low weight – Small size

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Table 4.1 (Continued)

	Application Class	Power Range	1980 Market Size (Annual)	Qualitative Requirements
G.	Mobile Light Duty			
	Passenger Car	20-110 kW	6,527,800	– Low cost – Small size – Low weight – Low emissions – Good load following – High reliability – High efficiency
	Agricultural Eq. Self-Powered	9-425 kW	36,600	
H.	Mobile Heavy Duty			
H.1.	Small (1-110)			– Low emissions – High efficiency – Fuel switching – Long life – Good load following
	Agricultural Tractors	15-110 kW	144,700	
	Trucks	60-110 kW	1,745,900	
	Construction Equipment	1-110 kW	213,400	
	Marine: Pleasure & Light Commercial	2-110 kW		
	Mining: Surface	20-110 kW	1,500	
	Mining: Underground Forestry Equip.	22-110 kW	400	
	Railroad Maintenance	22-110 kW	300*	
H.2.	Large (110+)			
	Agricultural Tractors	110-350 kW	43,300	
	Trucks & Buses	110-400 kW	1,152,100	
	Construction Equipment	110-560 kW	41,700	
	Marine: Pleasure & Light Commercial	110-350 kW	58,300	
	Locomotives	75-2250 kW	Small	
	Tactical Vehicles	60-300 kW	8,700	
	Military Tanks	1,120 kW	720	
I.	Solar Thermal and Thermal Storage Power Applications		– Several dozen demonstrations in operations – Large potential contingent on technology developments	– Reliable – Long life – High efficiency – External heat source – Low maintenance – Low cost – Low noise and vibration
I.1.	Solar Power Pumps			
	Solar Powered Pumps Solar Powered Compressors Solar Powered Alternators	~ 10-100 kW		
	Dish Mounted Generators	~ 10-50 kW		

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Table 4.1 (Continued)

	Application Class	Power Range	1980 Market Size (Annual)	Qualitative Requirements
I.2.	Thermal Storage Applications (Underwater)			
	Mining Submarine	~ 10-200 kW	NCP**	
	Military Submarine			
	Pleasure Boat Total Energy Sys.			
	General Purpose Submarine			
	Research Submarine			
	Off Shore Exploratory Submarine			
	Unmanned Surveillance Submarine			
	Short Term Underwater Plant			
I.3.	Thermal Storage Applications (Land Based)			
	Shopping Car	~ 1-50 kW		
	Regenerative Braking System for HD vehicles			
	Hybrid Vehicle			
	Wheelchair			
L.	Large Multifuel			
	Municipal Power Generation		< 1000	– Multi-fuel use
	Industrial Cogeneration	1000-5000 kW	< 1000	– Long life
	Gas Pipeline	1000-5000 kW		– Low maintenance
				– High efficiency

*Estimates.
**NCP – No commercial practice.

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F. Military

Fuel switching, fuel efficiency, low noise and vibration, load following and startability are important, as are small size, low weight, low maintenance and long life. Low emissions, heat recovery and low cost are not as critical.

G. Mobile Light Duty

Nearly all factors mentioned previously are important in light mobile power applications, particularly emissions, cost, and load following.

H. Mobile Heavy Duty

In medium duty mobile power applications, fuel switching and efficiency, low emissions, long life and good load following are important, but heat recovery, low engine cost and weight are not as important as for the light duty mobile power.

I. Solar Thermal and Thermal Storage Power

Most solar thermal power units employing Stirling engines assume that thermal energy storage is incorporated with the solar receiver in order to reduce problems associated with transient operation. The Stirling engine would, in fact, be operating from thermal storage. These seemingly diverse applications are, therefore, grouped together since they could be served by a common class of engines design to operate from a high temperature thermal storage media. In these applications, efficiency, low maintenance, long life, low cost, and reliable startability are important. Low emissions don't apply and fuel switching as well as heat recovery are not critical.

J. Large Multi-Fuel

Large stationary power systems generally operate with a high duty cycle. The critical characteristics of these systems will be high thermal efficiency and a multifuel capability. Both these characteristics lead to lower fuel operating costs which are a dominant cost factor with high duty cycle equipment. Other characteristics such as low size and weight, and good startability are not particularly important.

5.0 CONVENTIONAL ENGINE MARKETS AND PERFORMANCE CHARACTERISTICS

Most applications being considered for Stirling engines are presently being served or could be served by one or more conventional engine system. As a practical matter, Stirling engines will have to show some combination of technical and/or economic advantages to displace the conventional engines now utilized. It is, therefore, important to have an understanding of the market for conventional engines and the characteristics of engines now used in major market segments in order to evaluate the prospects for Stirling engines in each application class. In recognition of the above, this section of the report provides:

- o A brief overview of the market for conventional engines.
- o A summary of the salient operating characteristics and cost for widely used conventional engines.
- o The selection and description of a "representative engine" which would be typical of the competition in each application class.

5.1 Current Engine Sales

Table 5.1 summarizes the United States sales of engines in the power range from 0.5 to 5000 hp in 1978. The total number of engines sold annually is about 26 million. Of these about 25.6 million (98%) are spark ignition engines and about 0.62 million (2%) are Diesel engines. In addition, a small number of gas fired reciprocating engines (about 1500) and gas turbines (about 1500) are also sold in this power range.

Figure 5.1 shows a detailed sales breakdown of spark ignition engines in the 1-300 hp range, by rated power output for the year 1980. Approximately 92% of all such engines have rated outputs below 150 hp. Within this engine class there are two types of engines which account for nearly 87% of all engines sold:

- o Over 12 million engines with capacities of under 10 hp are sold annually. These are typically low usage engines used in such widespread applications as lawn mowers, chain saws, and snow blowers. The major portion of these engines are provided by either Briggs and Stratton or by Tecumsah.

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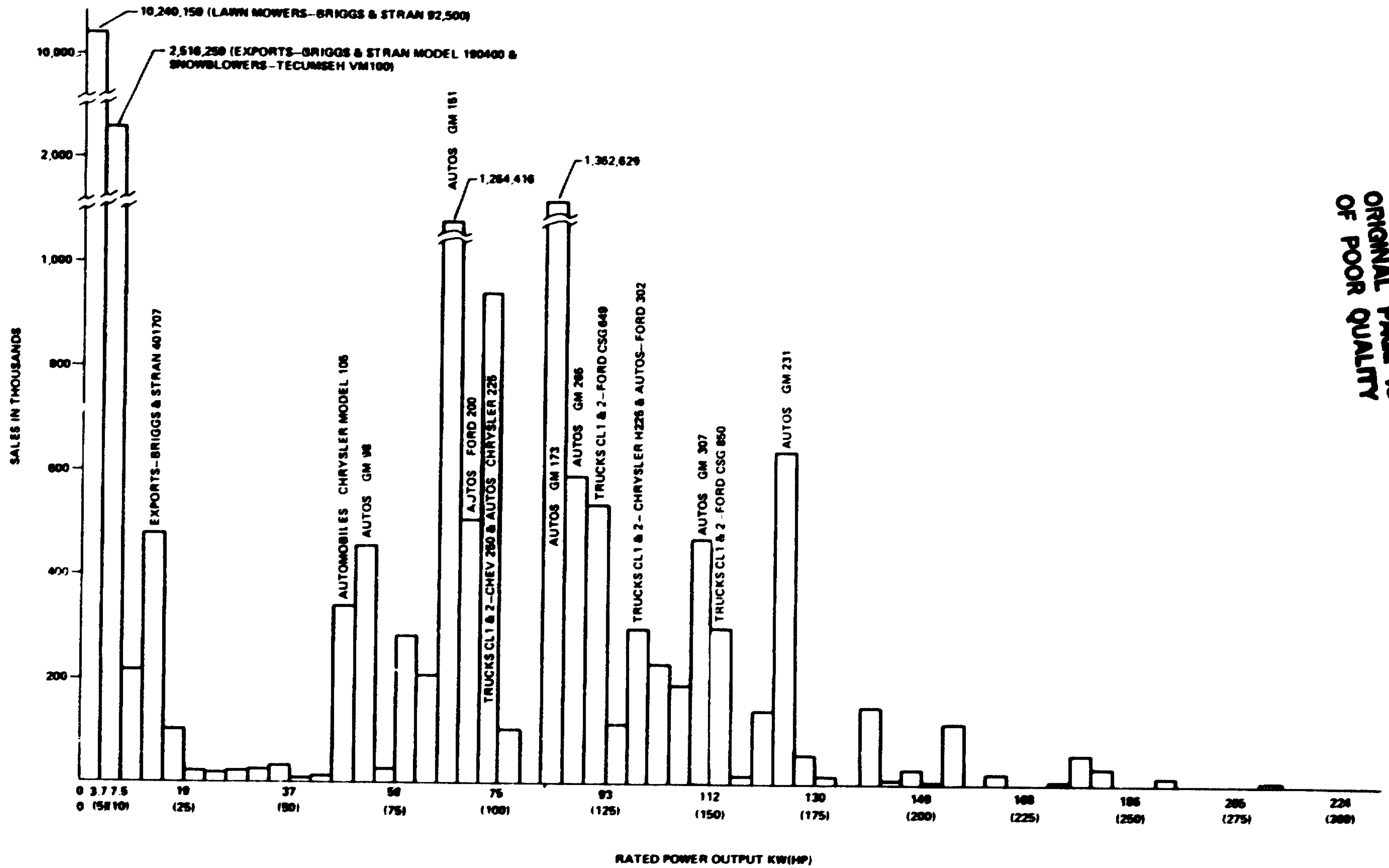
Table 5.1

U.S. ENGINE PRODUCTION; 1/2 TO 5000 HP, 1978

	Spark Ignition Non-Automotive	Spark Ignition Automotive*	Diesel Non-Automotive	Diesel Automotive	Gaseous Fuel Only	Gas Turbine
TOTAL	13,740,777	11,864,643	388,438	227,543	<1500 est.	<1500 est.
RATED RPM						
<1500	178,846				<1500 est.	
1501 - 2999						
3000 - 3999	13,561,931	11,864,643	388,438	227,543		
>4000						<1500 est.
METHOD OF COOLING						
Air	13,504,068		19,423			<1500 est.
Liquid	236,709	11,864,647	369,016	227,543	<1500 est.	
NUMBER OF CYLINDERS						
1	13,245,778		15,886			
2&3	231,714		17,373			Not applicable
4	110,690	759,205	106,068	415*	<1500 est.	
6	38,384	3,405,456	205,100	133,074*		
8 and up	114,211	7,699,982	44,011	94,054*		
DISPLACEMENT						
in^3 / cc						
<20 / 328	12,348,283					
20 - 75 / 328 - 1230	1,051,832		20,816			
76 -150 / 1230 - 2460	36,990	298,981				Not applicable
>150 / >2460	293,672	11,565,662	367,622	227,543	<1500 est.	

* Estimated from sales data

Source: U.S. Department of Commerce, Power Systems Research, Forecast Associates Inc, Arthur D. Little, Inc. Estimates



Source: Arthur D. Little, Inc.

FIGURE 5.1 1980 US SALES OF GASOLINE ENGINES 1-224 KW (1-300 HP) AND SALES LEADING ENGINES AND APPLICATIONS

- Over 7 million engines are produced annually with rated power outputs of between 60 and 150 hp for vehicular applications. Most of these are for automotive use. However, a significant number are also used in such applications as light trucks, and tractors. Over 1/2 dozen manufacturers (primarily automotive companies) participate in this market area.

Figure 5.2 shows the detailed sales breakdown of Diesel engines by rated output in the under 400 hp range. The sales distribution of Diesel engines is seen to be more evenly distributed than for spark ignition engines. Widespread applications for Diesels indicated on Figure 5.2 include compressor drives, farm equipment, and generator sets. However, approximately 60% of Diesel sales are for automotive and truck propulsion applications.

Within the power range covered by Figures 5.1 and 5.2, the reciprocating internal combustion engines are similar in design and concept. Many are versions of automotive engines which achieve their rated power at relatively high crankshaft speeds (over 1,200 rpm) and are commonly referred to as "high speed engines".

High speed engines in the 400-1000 hp range are not a large share of the market. The number of units sold annually is estimated to be less than 1000 units per year.

Engines with power outputs in excess of 1000 hp generally are operated at lower speeds. The lower speeds are usually dictated by large cylinder bores and longer operating life requirements. The industry classifies these as low speed (up to 400 rpm) and medium speed engines (400-1200 rpm).

Table 4.1 includes an estimate of engine sales in this range. The total volume of engines is less than 2000 units per year. Major uses for these larger engines are for marine propulsion, locomotives, municipal generating stations, and gas pipeline compressor stations.

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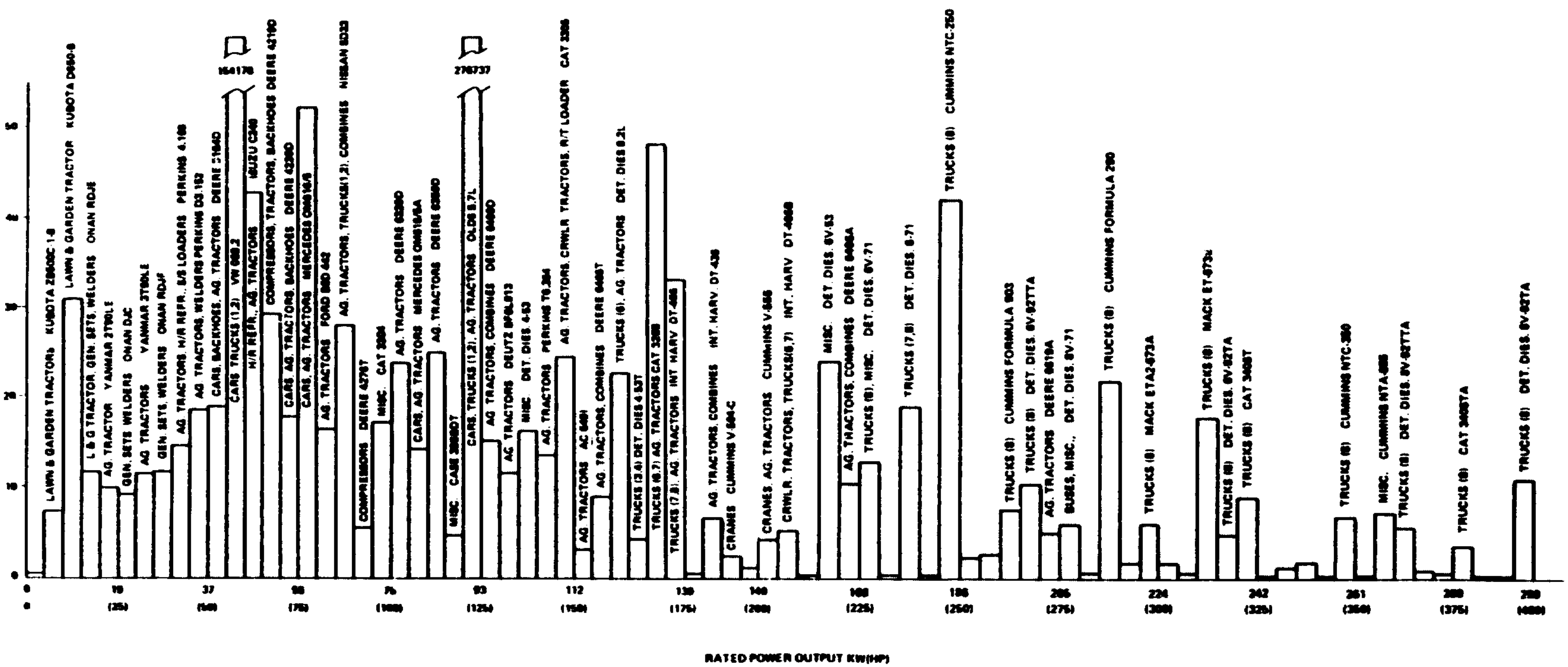


Source: Arthur D. Little, Inc.

FIGURE 5.2 1980 US SALES OF DIESEL ENGINES, 1-298 KW (1-400 HP) AND SALES LEADING ENGINES AND APPLICATIONS

5.2 Engine Cost and Performance Characteristics

There is a wide range of engines now in use with over 50 manufacturers producing, at least, 670 engine models. However, within broad engine categories (small low usage, automotive, low speed Diesel, etc.) the technical characteristics of engine types fall within a relatively narrow band. This fact is reflected in the highly competitive nature of the engine business where relatively modest differences in performance or cost can influence sales.

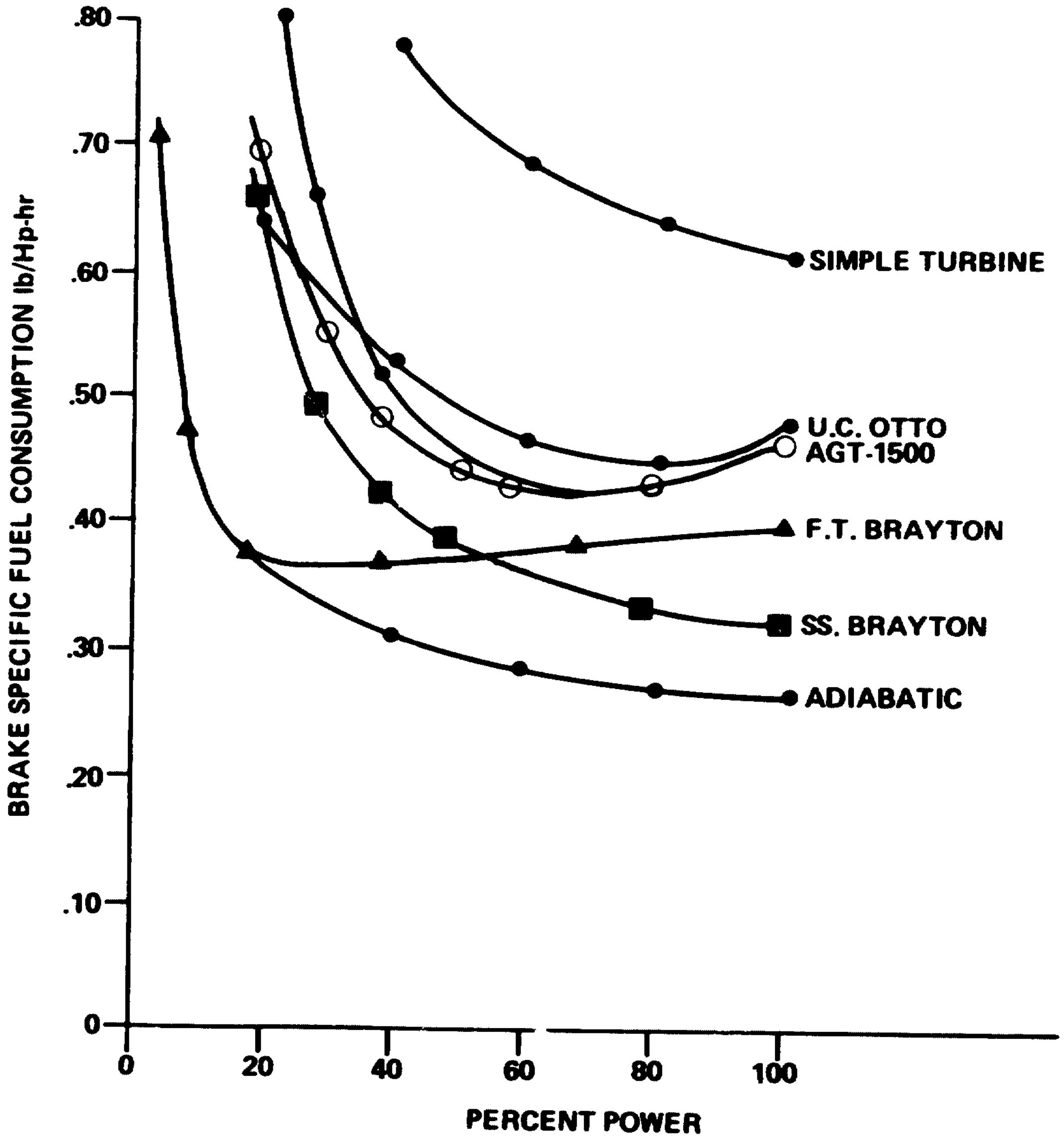
The United States Army has compiled a useful display of the characteristics of some specific engines used in a range of military applications. Figures 5.3 through 5.6 present their plots of specific fuel consumption (related to engine efficiency), power to weight ratio, specific volume, and costs for a wide range of engines under 1500 kW (2000 hp).* These plots include gas turbines, as well as projections for the adiabatic Diesel under test at Cummins. They indicate a rather wide range performance between different categories of engine system. For example, there can be over a two to one difference in any parameter depending on engine type considered. This further emphasizes the importance of realistically assessing which types of conventional engines Stirling engines will have to compete against in each application.

Low Usage Engines:

The most important characteristic of these small, mass produced, spark ignition engines are their very low cost (<$50/kW), small size, and low weight. These are all critical for the types of applications in which these engines are normally used.

The relatively short life (typically 500-1000 hours) and poor fuel efficiency (10-15%) of these engines does not strongly detract from their capability to function adequately in their most common applications. For example, a useful life of 500 hours represents over 10 lawn cutting seasons in a typical lawn mower application.

* Data compiled from a series of unpublished communications and presentations to Department of Transportation personnel by TARADCOM.



Source: TARADCOM

Figure 5.3 Typical Fuel Consumption of Engines under 1500 KW (2000 HP)

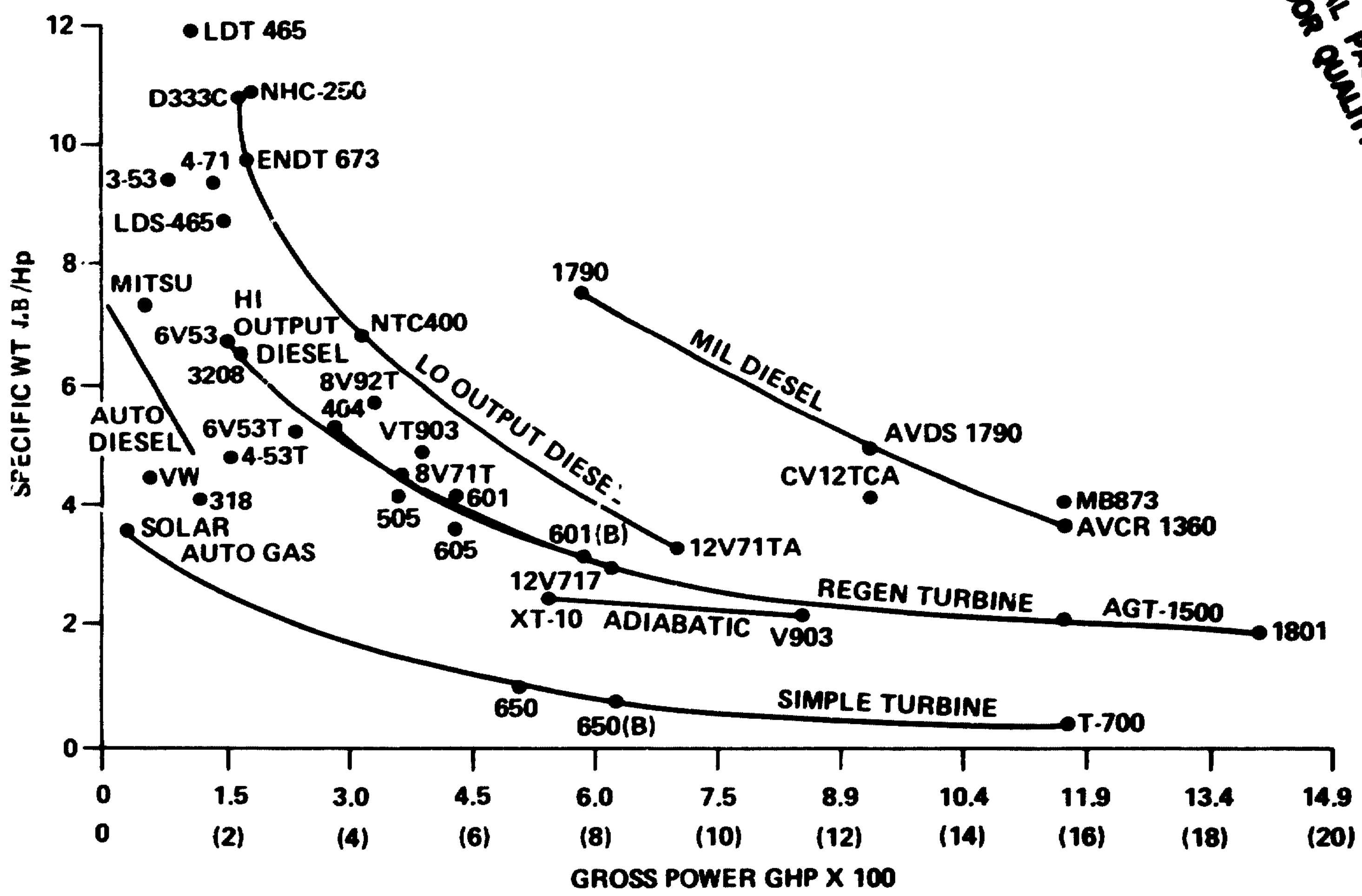


Figure 5.4 Typical Specific Weight of Engines Under 1500 KW (2000 HP)

Source: TARADCOM

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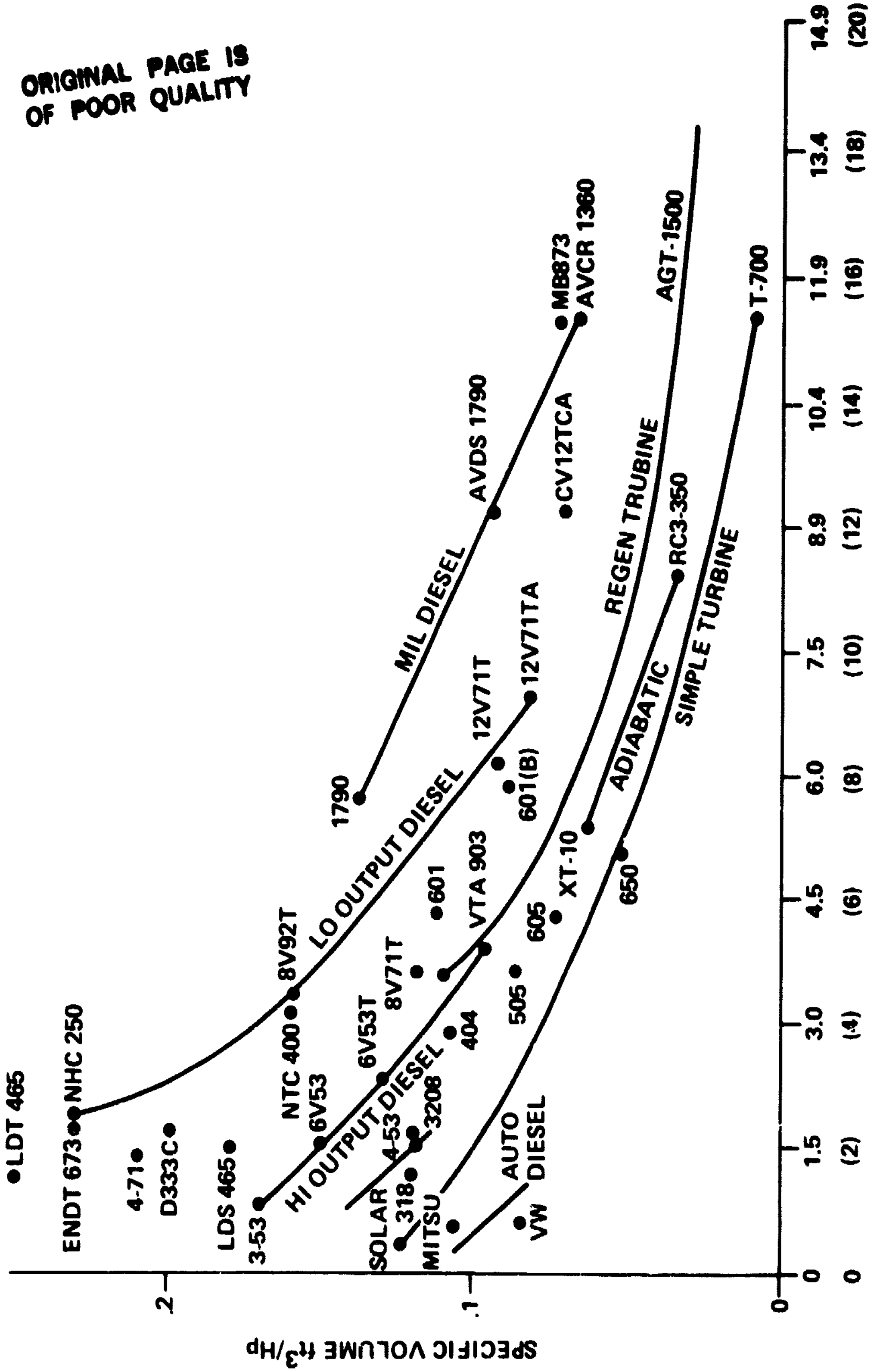

Source: TARADCOM

Figure 5.5 Typical Specific Volume of Engines Under 1500 KW (2000 HP)

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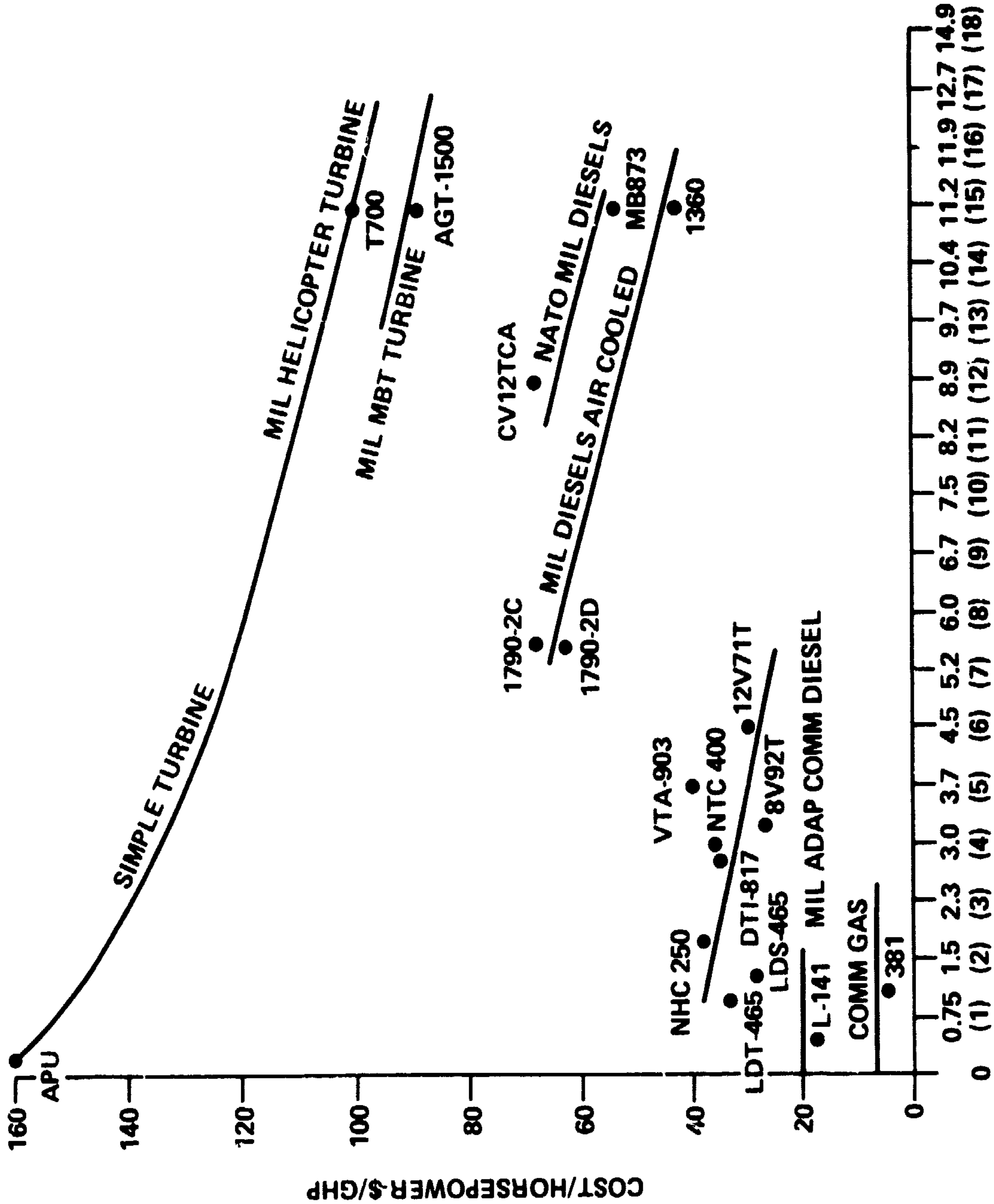

Figure 5.6 Typical Costs of Engines Under 1500 KW (2000 HP)

Source: TARADCOM

Automotive Engines (Spark Ignition):

As with low usage engines, spark ignition automotive engines have a cost of \$25-30/kW. This low cost reflects both the economics of mass production and the relatively modest operational life (3000-4000 hours) required of such engines. The modest life goals, in turn, allow for higher operational speeds (higher rated outputs) and lighter weight construction.

The efficiency indicated is in the 25-30% range. This efficiency range is at the lower end of that expected from Stirling engines, which would provide the Stirling engine with a fuel economy advantage.

The emission levels indicated for the automotive engine satisfy present Federal regulations and will continue to do so under proposed low (see Section 6.0).

High Speed Diesels:

This class of engine includes those now used in automotive applications, which are estimated to cost \$25-40/kW. Non-automotive engines have a significantly higher cost (\$150/kW to \$300/kW) than their spark ignition counterparts. Benefits derived from this significantly higher cost include higher efficiency, in the 30% to 35% range, and longer life, (up to 20,000-30,000 hours). The higher cost of these engines facilitates establishing a competitive position for Stirling engines in applications which they serve. Recent systems studies at NASA indicate that the efficiency of a well developed Stirling engine may be better than Diesels in the high speed range. In addition, Diesel engine emissions include particulates which are not now covered by regulations. As indicated in Section 6.0, there is a great deal of concern about the health hazards of the particulates, which may result in additional regulations, thereby enhancing the competitive position of the Stirling engine.

Medium and Low Speed Diesels:

These engines are typically used in applications where long life and high reliability is required. The resultant robust construction and the low production quantities lead to engines with relatively high costs in the \$200-500/kW range.

The fuel efficiency of these engines is generally very high (35-40%) and, in addition, some engines in this class have a limited multi-fuel capability. Typically, the same model can be set up as either a Diesel, gaseous, dual or even tri-fuel engine. Diesels are run on anything from No. 2 Diesel down to the heavy distillates such as Bunker "C". The more common gaseous fuel is natural gas, although all sorts of other combustible gaseous fuels such as sewer gas have been used.

Dual or tri-fuel engines have in the past been typically compression ignition engines using a liquid fuel injected as in a normal Diesel to ignite a carburetored (pre-mixed) gaseous fuel. These dual fuel engines get about 10% of their total energy from the liquid fuel, the remainder from the gaseous fuel. They are used where the extra reliability and extended maintenance intervals of a Diesel are desired, but where it is inconvenient or uneconomical to run the engine entirely on a liquid fuel. Lately, true dual fuel engines, where the fuel injectors are replaced with a spark plug system, are coming into more widespread use.

These engines are usually relatively heavy and bulky as compared to the "high speed" engine classes. For example, their specific weight is typically in the 10-30 kg/kW range as compared to spark ignition automotive type engines with specific weights of 2-4 kg/kW. Consequently, there will be considerable flexibility in the physical design of Stirling engines (size, weight, layout) when used in applications now served by low speed internal combustion engines.

A very important feature of engines in this class is their high reliability as measured by maintenance intervals and useful life. Many engines in this class have lives in excess of 20,000 hours (time to major overhaul) and will operate with maintenance intervals of 1,000 hours to 2,000 hours. The exceptional reliability is in a totally different class than that achieved or needed by automotive engines and could be one of the more difficult goals to be met by a new engine development.

Gas Turbines:

The market for gas turbines under 3730 kW (5000 hp) is extremely limited. The primary reason for this is their relatively high initial cost ($150-300/kW) and poor efficiency (20-25%), when purchased in physically small sizes and moderate turbine inlet temperatures (i.e., about 1700°F). The high cost is due to requirements for expensive (difficult to machine and join) materials in the combustor and turbine (e.g., Inconel), close tolerances required, difficult to machine shapes, and fine surface finishes required for the vanes and blades.

Gas turbine units generally start well after long dormant periods, but take longer to reach power than reciprocating engines. Problems with compressor choking hinder initial start-up, and thermal inertia hampers the larger regenerated units. While some units can achieve full power within 30 seconds, some units require as much as 30 minutes.

The power density of gas turbines is generally a factor of 10-100 better than the slow speed reciprocating engine against which they compete.

Gas turbines also possess an extremely long life and extended maintenance intervals. Lives of 60,000 hours plus between overhauls have been quoted, as have maintenance intervals of 30,000 hours.

Like other types of engines, gas turbines possess a limited multi-fuel capability. They are, however, more sensitive to the fuel quality, as combustion products loaded with abrasive particulates can have a detrimental effect upon the turbine component life. Generally speaking, gas turbines can be set up to run on the same fuels as the large reciprocating engines.

More details of the multi-fuel capability of conventional internal and external combustion engines appear in Section 8.0.

Rankine Engines:

One of the attributes of a Stirling engine is its potential to operate using solid fuels and the capability to utilize non-conventional heat inputs (solar, nuclear, thermal storage). While Diesel and gasoline engines, and to a lesser extent, turbines do not offer this advantage, Rankine engines can use solid fuel heat sources and hence wider multi-fuel capability is available in such engines. Therefore, Rankine engines are likely to be in competition with Stirling engines in many applications of interest. One difference between a Stirling engine and a Rankine engine may be that efficiencies attainable in small Rankine systems (less than 100 kW) are generally considerably lower (at 15-25%) compared to projected efficiencies of 30-40+% for similar size well developed Stirling systems.

At present, Rankine steam power plants are mostly used by utilities for generating hundreds of Megawatts of power. However small Rankine systems (ranging from 10 kW up to 15,000 kW) are increasingly considered for many applications. The smaller Rankine systems (10 kW up to 5,000 kW) utilize various heat sources including:

- Solar energy.
- Waste heat from Diesel plants or furnaces.
- Oil and gas (in packaged boilers).
- Geothermal.

Rankine cycle engines require relatively large amounts of heat transfer area and relatively complex series of expanders, pumps, and controls for their operation. As such, the limited practice to date has resulted in relatively high costs in the $1,000-3,000 per kW range. Projections for larger production quantities are in the $500-1500 range, depending on capacity and operating temperature.

5.3 Selection of Representative Engines

Once the application classes were defined (see Section 4.0) the sales leading engines for that class were determined from data compiled by Power Systems Research. A summary of this data appears in Appendix C. In many cases, more than one type (i.e., Diesel, spark ignition, 2-cycle or 4-cycle) made up a significant portion of the total engine sales within an application class. When this occurred, the sales leading engine of each type was identified.

Table 5.2 specifies a specific conventional engine which would be typical of that either used or which could be used in each application class. Engine capacities were selected to emphasize those applications within each class with the largest potential markets. Performance and cost information is presented for each representative engine to provide a benchmark by which to judge Stirling engines in those applications. Also noted is the production volume of the representative engine.

As suggested by Table 5.2, there is no single set of technical or cost goals which must be achieved by Stirling engine systems. For example, automotive applications set particularly stringent cost requirements on the Stirling engine (about $25/kW) but only requires 2,000-3,000 hours of operational life, which allows additional flexibility in the choice of hot section materials and system design. In contrast, a heat pump application might allow costs 4 to 5 times those of an automobile engine but would require a useful life of over 20,000 hours.

As noted on Table 5.2, there are some applications where there is no present commercial practice, with conventional engines. These applications include nuclear/space power and solar power. For these application classes the possible competitive engines were selected as thermo-electrics, Brayton cycle, and Rankine cycle engines, respectively. This selection reflects the limited practice to date in these application areas. Appendix C.3 has additional information on medium and low speed Diesels, gas turbines, and Rankine cycle engines.

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Table 5.2

CHARACTERISTICS OF REPRESENTATIVE CONVENTIONAL ENGINES FOR EACH APPLICATION CLASS

Application Class	Engine Manufacturer	Model	Fuel	Cont. Power at Speed kW/RPM	Power @ 2400 RPM kW	Emissions, g/kWh HC	CO	NO_x	Efficiency	Coolant Type/ Flow Rate ℓ/min	Maintenance[6] Interval Hours	Life[6] Between Overhaul/hrs	Startability Minutes[5]	Cost[4] (Price) $/kW	Weight kg/kW	Size $(m^3/kW)x10^3$	Production Volume Units
1. Heat Pump & Total Energy	Caterpillar	3304	Diesel[1]	70 @ 1800	63				34%	Water/151	1,000	30,000	2-4	110-125	10.3	14.6	13,000
2. Industrial Equipment	Briggs & Stratton	190400	Gasoline	6.0 @ 3600	4.5	5.4*	142*	5.2*	10-15%*	Air[1]	25-50	1,000	3-6	45	3.40	4.42	498,380
	Continental	F-163	Gasoline[3]	43.2 @ 2800	41.4					Water/128*	150-250	17,500	2-4			5.87	7,500
	John Deere	4219D	Diesel	36 @ 1800	52.0				33%	Water/155	500-700		2-4	55-65	10.63	9.61	20,000
3. Spare Power	Note 8																
4. Long Run Remote, Potentially Multi-Fuel	Lister	JA6	Diesel	103 @ 2800	92				41%	Air[1]	1,000	25,000-30,000	3-6	110-125	9.24	11.6	130
	Thermo-King	C201	Diesel	9 @ 2200					28%	Water/	1,200	20,000	2-4	277	55.6	29.9	15,000*
5. Low Usage Equipment	Briggs & Stratton	92500	Gasoline	2.2 @ 3600	2.0	5.4	142	5.2	10-15%*	Air[1]	25	200-400	3-6	50	4.13	8.45	1,080,800
	Wisconsin Teledyne	VH4D	Gasoline	22 @ 2800	20.8					Air[1]	100	7,500	3-6		7.64	17.1	8,500
6. Military	Detroit Diesel	6V-53	Diesel	161 @ 2800	151					Water/	1,000-2,000	10,000-15,000	2-4	45-50	4.19	5.87	10,700
7. Mobile Light Duty	GM	173CID	Gasoline	82 @ 4800	49	0.166[2]	4.23[2]	0.55[2]		Water/	150-250	2,000-3,000	2-4	9-23	4.7		636,500
	John Deere	6466D	Diesel	78 @ 1800	NA				32%	Water/284	1,000-2,000	5,000-10,000	2-4	55-65	9.45	7.73	6,700
8. Mobile Heavy Duty	John Deere	6329D	Diesel	52 @ 1800	76				34%	Water/178	1,000-2,000	5,000-10,000	2-4	55-65	9.98	9.28	11,800
Small	Ford	CSG649	Gasoline	93 @ 3600	73	0.71[2]	4.2[2]	1.34[2]		Water/	150-250	2,000-3,000	2-4	9-23	2.31	4.66	329,000
Large	Ford	CSG850	Gasoline	113 @ 4000	98	Note 7				Water/	150-250	2,000-3,000	2-4	9-23	2.18	3.05	302,800
	IH	DT-414	Diesel	112 @ 2400	112	Note 7				Water/306	1,000-2,000	8,000-12,000	2-4	50-60	5.9	8.38	7,100
9. Solar & Thermal Storage	Note 9																
10. Large Stationary Power																	
Diesel	Colt-Fairbanks Morse	38-TD	Diesel, Gas Heavy Distillate, etc.	3000 @ 900	–	0.0	1.3	13.0	37%	Water/	10,000-20,000	100,000+	10-30	250	10.6	15.0	< 200
Gas Turbine	Detroit Diesel Allison, Div. of GM	501KB	Kerosene, J Series, Diesel, etc.	3120	–	0.045	1.27	10.0	24%	Air	10,000-20,000	80,000	10-30	125	0.17	0.32	< 1,500**
Steam Rankine	Thermo Electron/ Peter Brotherhood		Coal, Oil, Gas, etc.	1,000-15,000	–				15-25%	Air/Water	10,000-20,000	100,000+	10-30	650			< 200

1. Natural convection only – no pump.
2. Grams per mile, one EPA cycle, light duty.
3. Engine has multi-fuel capability.
4. Selling price to user.
5. At 75°F, estimated.
6. Depends upon operating environment and quality of service. Estimated based on expected service within application.
7. Meets current HD truck emission standards of less than 25 gms/bhphr CO, 5 gms/bhphr HC + NO_x.
8. Limited experience to date in space thermal systems use thermoelectrics. Most common present practice for space power in photovoltaics.
9. No commercial practice. Solar power demonstrations often use organic Rankine engines.

*Estimated based on experience with similar engines.
**Includes sales of gas turbines for aircraft applications.

Source: Arthur D. Little, Inc.

6.0 STATUS OF STIRLING ENGINE SYSTEMS

6.1 Background

The closed cycle, regenerative Stirling engine concept was initially developed by Robert Stirling in 1816. In the late 1800's and early 1900's several thousand hot air engines operating on a simplified version of the Stirling cycle were manufactured. These relatively heavy and inefficient engines could operate on coal, charcoal, or wood to produce power for water pumping and remote applications. Virtually all hot air Stirling engines were eventually replaced by more efficient and compact steam power systems.

The modern era of Stirling engine development began in the mid 1930's at Philips in Holland. The initial effort was to develop a low power (0.2 kW) generator for powering radios in remote areas. Latter developments emphasized vehicular propulsion systems. Over the ensuing 45 or more years, over 8 major companies have been involved in Stirling engine development programs. However, as indicated in Figure 6.1, there have been only two primary developers of kinematic Stirling engines, Philips and United Stirling. All other developments, including those in the United States, are the result of a complex series of license and joint venture agreements between the companies involved.

The development of free piston engines is relatively recent and was initially spurred by the programs of W. Beale at the University of Ohio. Subsequently, free piston engine activities have been undertaken at Mechanical Technologies, Inc., General Electric, University of Washington, and ERG. These other activities are, however, in large part based on earlier work by Beale.

Even though Stirling engines have been under development for over 40 years, it is estimated that less than 500 Kinematic engines have been built and fewer than 50 free piston engines have been built. As a practical matter, there have been very few different basic engine configurations built and tested. This, in part, reflects the tendency to utilize the few key personnel and organizations with extensive Stirling engine experience in developing more advanced engine systems. It may, however, have the effect of limiting the flow of new ideas and personnel into the field.

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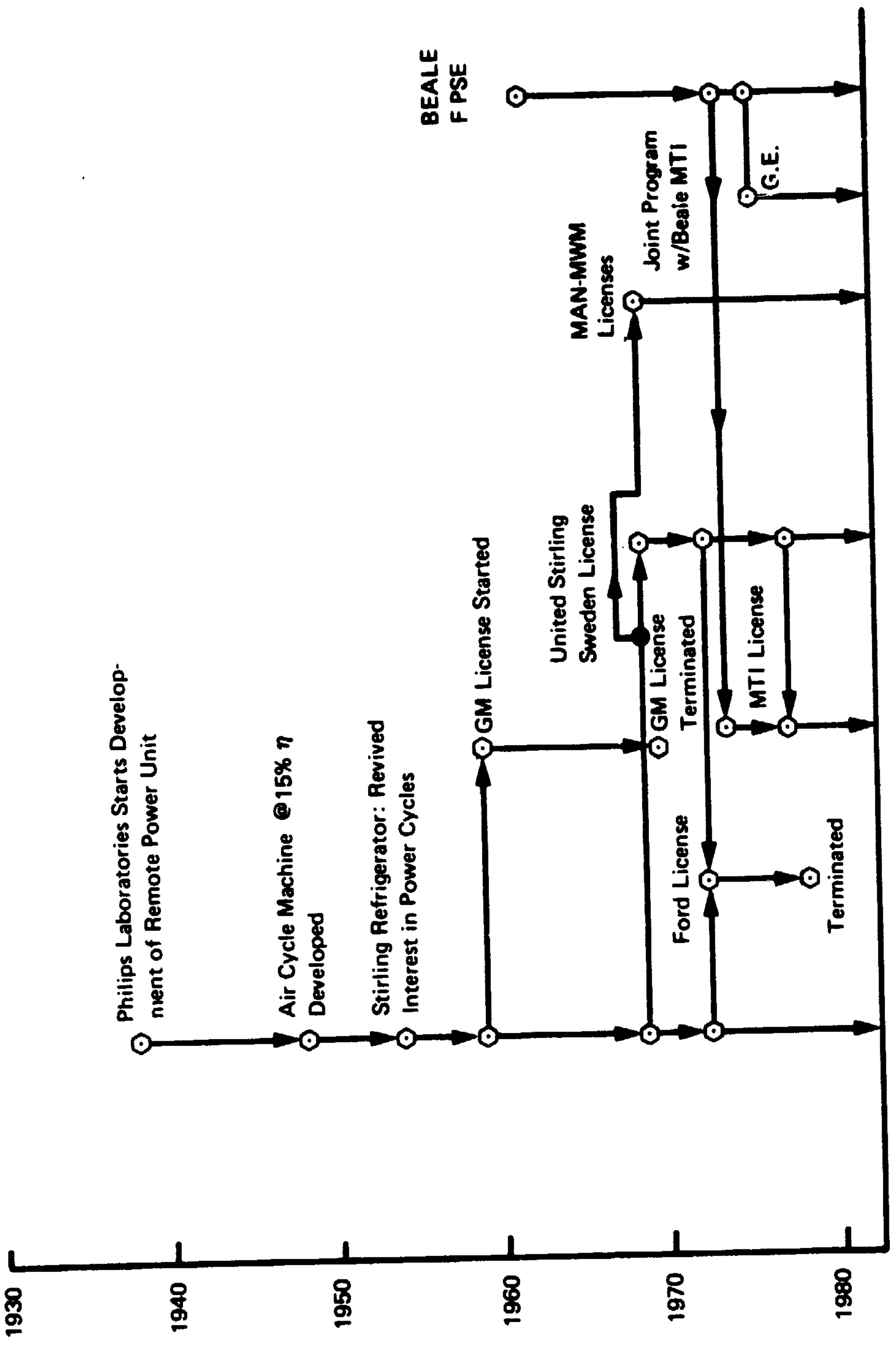

FIGURE 6-1 HISTORICAL DEVELOPMENT OF STIRLING TECHNOLOGY

More detailed overviews of the history of Stirling engines can be found in References 1-4.

The objectives of the following sections are to:

- o Provide an overview of the operational characteristics of Stirling engines tested to date and the extent to which actual performance has demonstrated the Stirling engine advantages indicated in earlier sections.
- o Identify those factors which are limiting the performance of Stirling engines as now designed.
- o Review steps being taken to rectify identified problem areas.

This information will be used to make judgements on the probable near and longer term performance levels of Stirling engines and to identify R&D activities needed to result in competitive Stirling engine configurations.

6.2 Kinematic Engines

The most extensive recent experience that is well documented with kinematic Stirling engines has been achieved with those based on the 4-95 (P-40) engine designed by United Stirling of Sweden. Various modifications of this engine have evolved over a period of seven years and it is the basis of the MOD-I engine, being developed as part of the DOE/NASA Advanced Automotive Stirling Engine (ASE) Program, and a solar operated engine, which recently initiated testing as part of the JPL solar thermal/parabolic dish program.[5,6] This engine, shown in Figure 6.2, is a four-cylinder, double acting configuration which can produce 40 kW (55 hp) under design conditions (Table 6.1). As of January, 1981, 21 engines of this basic design had been built and over 13 thousand hours of operation had been accumulated.[7] As indicated later, however, the accumulated hours of operation have usually entailed numerous unplanned shutdowns and the reliability of critical subsystems (primarily seals and heater head) are still in question.

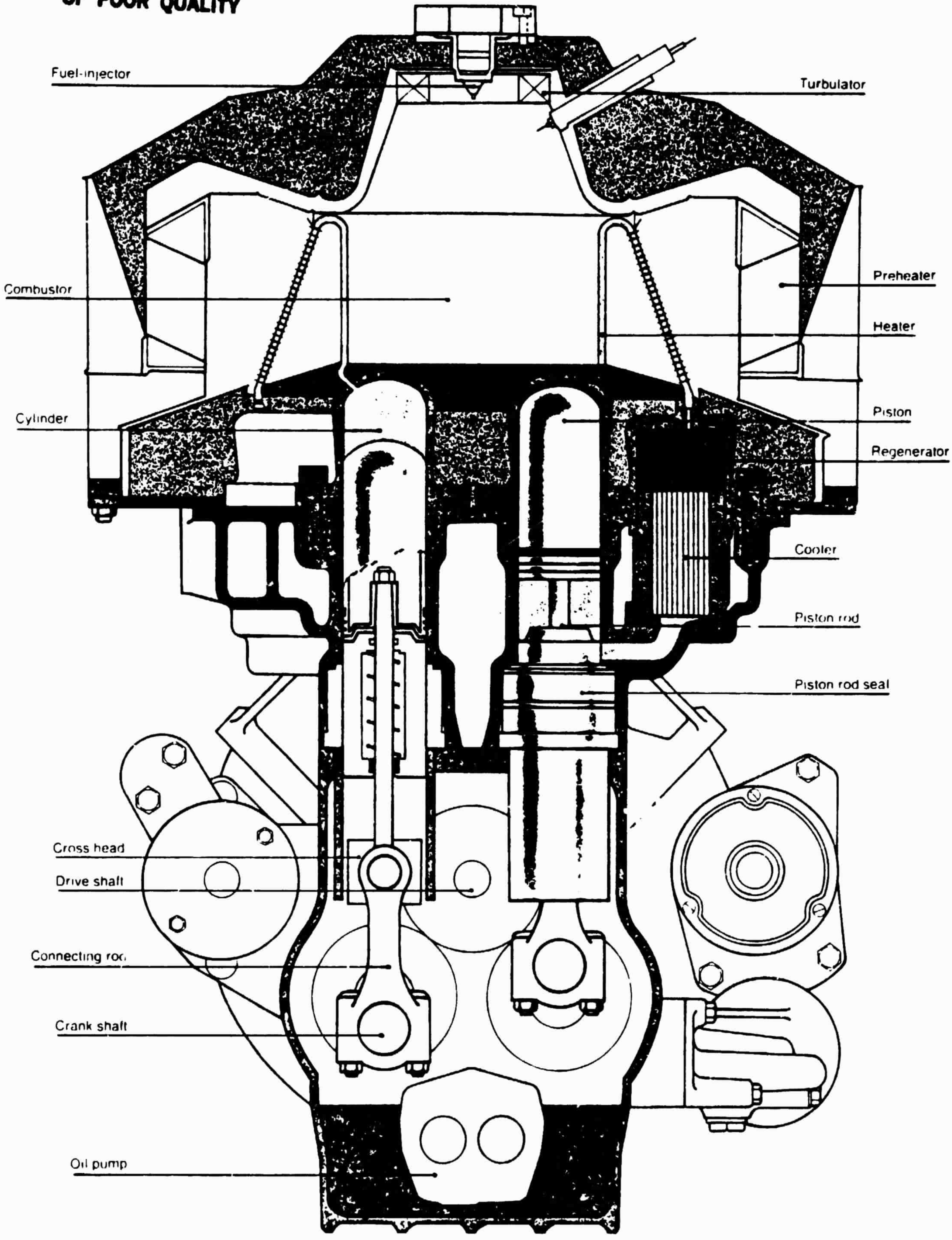

Figure 6.2 UNITED STIRLING OF SWEDEN 4-95 (P-40) ENGINE

Table 6.1

DESIGN/PERFORMANCE SPECIFICATIONS OF THE 4-95 STIRLING ENGINE

Overall Dimensions	785 x 655 x 580 mm
Dry Weight (including zuxiliaries)	329 kg
Brake Power[a] at 4000 rpm	≈40 kW
Brake Thermal Efficiency at 2000 rpm	≈29%
Working Gas	Hydrogen
Working Gas Mass[b]	<100 g
Number of cylinders	4 (square 4 arrangement)
Displacement	0.38 l
Bore	55 mm
Stroke	40 mm
Drive	Dual crank, crankshafts geared to driveshaft
Method of Power Control	Mean cycle pressure modulation (15 MPa, max)
Fuel	Unleaded regular gasoline or diesel fuel
Range of air-fuel Ratio[c]	15 to 25
Heater Type	Involute Tubular
Number of Tubes	72
Number of tubes per quadrant	18
Heater Materials:	
Tube	Multimet N-155
Cylinder and Regenerator Housings	Haynes Stellite HS-31
Preheater Type	Recuperative
Number of Regenerators/Coolers per Engine Cylinder	2
Regenerator Material	304 Stainless Steel Wire Mesh Gauze
Piston Rod Seal Type	Sliding (Pumping Leningrader)
Piston Rod Seal and Piston Ring Material	RULON LD (filled PTFE)

a. Mean cycle pressure, 15 MPa; heater temperature, 720°C; cooler temperature, 50°C.
b. Including gas in storage bottle.
c. Controlled by Bosch K-Jetronic continuous fuel injection system.

SOURCE: Reference 8

Most of the following commentary on the performance characteristics of kinematic Stirling engines is based on the 4-95 engine and its more recent derivatives. However, reference is also made to earlier Philips engines, where this experience helps to illustrate specific Stirling engine characteristics of interest.

Efficiency:

Stirling engine efficiencies of 30% have been consistently demonstrated on test and demonstration engines for over 15 years.[8,2] More recent tests with the MOD-I engine and solar version of the 4-95 have demonstrated efficiency levels in excess of 35% (including burner and parasitic power losses)[9,10]. Projections by NASA suggest potential automotive engines for efficiencies in the low 40% and in the high 40% for certain stationary applications of automotive derived engines which do not have the losses associated with a combuster subsystem, i.e., solar nuclear, and thermal storage. The efficiency capabilities of Stirling engines are, therefore, well-demonstrated, and further improvements might be expected, as higher temperature heater head materials are developed.

Multi-Fuel Capability:

The MOD-I engine has been operated on most liquid fuels (gasoline, Diesel, etc.) of near-term interest as a motor fuel.[11] Earlier work on Stirling engine generator sets (GPU-3, developed at G.M.) demonstrated the capability of Stirling engines to switch between a wide range of liquid fuels used in military field service.[1,12] Philips operated a biomass fired engine using a heat pipe heat transfer system[13] and more recently, Sunpower, Inc. has operated a simple hot air Stirling engine directly fired by charcoal and rice husks.[14,15]

The basic multi-fuel capability of a Stirling engine has, therefore, been extensively demonstrated, particularly when using liquid and gaseous commercial fuels.

The ability of large, high temperature, high efficiency Stirling engines to utilize coal has been the subject of several studies funded through the Argonne National Laboratories. These studies did not identify insurmountable technical barriers to the operation of the Stirling engine in this fashion. However, no experimental work has been done to date, in order to resolve the many serious issues associated with high temperature, high power density coal fired systems (fouling, corrosion, slagging, etc.).

As a practical matter the ability to burn coal will not influence the desirability of the Stirling engine in most applications since few power systems of less than 5000 kW utilize coal, due to the difficulty associated with coal handling and stack gas clean up.

Low Emissions:

One of the major incentives to the development of Stirling engines has been their potential for low exhaust gas emission operation. Since the combustion process takes place outside the working volume of the Stirling engine, the process is more easily controlled and can be carried out with less violent transients and in a more steady state fashion than in an internal combustion engine. This greatly simplifies control of the air/fuel mixtures and results in reduced emissions. The MOD-I engine has been extensively tested over automotive driving cycles and has resulted in emission levels as summarized in Table 6.2.[9]

These emission levels are well below those required of present and projected regulations (Table 6.2) and below those of competitive I.C. engines. Stirling engines have consistently demonstrated such low emission levels, in a system with good air/fuel ratio control and adequate combustor design.

Noise and Vibration:

Stirling engines have no valves, can be fully balanced, and use a continuous combustion process in their operation. As a result, they have low operational noise levels and minimum vibration. These attributes have been demonstrated on several engines including the MOD-I and the V160 engine of SPS. Both these engines demonstrated noise levels of less than 70 DB (a comparable Diesel can be over 90 DB)(16) and very low mechanical vibration levels. This characteristic makes the use of such engines in applications requiring low noise levels (heat pumps, indoor vehicles, etc.) particularly attractive.

Table 6.2

SUMMARY OF EMISSION GOALS FOR PASSENGER AUTOMOBILES

COMPARED WITH STIRLING ENGINE PERFORMANCE (gms/mile)

	FEDERAL EMISSION GOALS*	ASE DATA	
		CITY	HIGHWAY
Hydrocarbons (HC)	≤0.41	0.25	0.004
Carbon Monoxide (CO)	≤3.40	3.21	0.40
Nitrous Oxides (NO_x)	≤0.40	0.84	0.61
Particulates	≤0.20	0.087	0.008

* See Table 8.1 for actual standards currently in effect.

Startability:

Stirling engines require a number of auxiliaries for starting. In the automotive application, the engine has two starter motors, one for auxiliaries including the blower, atomizing air compressor and hydraulic oil pump and another to operate the starter.

The high energy flux of the combustion chamber/heater head subassembly is the source of considerable design difficulty. However, this high energy flux also results in allowing the engine to become operational very quickly from a cold start. Thus, there is no reason that the Stirling engine would be worse than Diesel or otto cycle internal combustion engines in terms of time to start and develop power. Tests on the automotive Stirling engine indicate the engine will be operational within 15 sec. at 85°F and 40 sec. at -20°F which compares well with an automotive Diesel (from 20-60 sec.).[5]

It appears, therefore, that the Stirling engine startability is comparable to that of I.C. engines (and probably better than that of Rankine cycle or gas turbine engines) and is sufficient for all applications of interest.

Part Load Operation:

In the Stirling engine, power output is proportional to the pressure and the swept volume of the engine and therefore there are two common methods of controlling the power output. One is to adjust the volume that is swept and the other is to adjust the mean pressure of the engine, usually in conjunction with a change in the rpm. Most Stirling engines to date are controlled by adjusting the gas pressure and rpm of the engine. These systems use a compressor and a storage bottle with check and control valves, in addition to short circuits to adjust the output of the engine. In most cases, the heater head temperature is maintained constant by varying the fuel flow to the combustor.

The alternative drive mechanisms mentioned in later sections vary the displacement of the engine with variable stroke drives through the use of swashplates, etc. These systems hold promise to improve the load following characteristics of the Stirling engine and decrease its complexity, but are not yet demonstrated technology in large sizes. Swashplate systems have been used in small compressors for a number of years, there is only limited experience in power transmission of over approximately 20 hp.

The part load operation of an engine is particularly important for vehicular propulsion applications. It can also be important in other applications such as generator sets, as well as utility and solar thermal power generation systems. Figure 6.3 shows curves of the part load power and efficiency of the MOD-I Stirling engine as a function of speed and pressure.(9) As indicated, the part load efficiency is excellent. Furthermore, the high efficiency is accompanied by very good torque characteristics.

The part load characteristics of Figure 6.3 were accomplished mainly by changing the working gas pressure to change power at constant operating temperatures. Similarly good part load characteristic are expected to occur when using a variable displacement arrangement to vary output.(17,18)

System Size and Weight:

Stirling engines developed to date have usually been somewhat heavier and larger than conventional engines, particularly in applications utilizing light duty Internal Combustion engines. This is due, in part, to the fact that most engines developed thus far have been demonstration type engines. It would appear that the continuous combustion process described above will result in smaller engines, since the power is generated smoothly, without rapid transients in the engine. In addition, high working gas pressures, high, continuous, heat flux rates, and short stroke, tend to make the size of the mechanical portion of a double acting Stirling engine (pistons and drive train) smaller than for an Internal Combustion engine of similar capacity. For example, the displacement volume of the automobile Stirling engine is approximately 30 in^3 (.38 in^3/hp) vs 100^+ in^3 (>1 in^3/hp) for a typical conventional engine in the same power range and application class (automotive).

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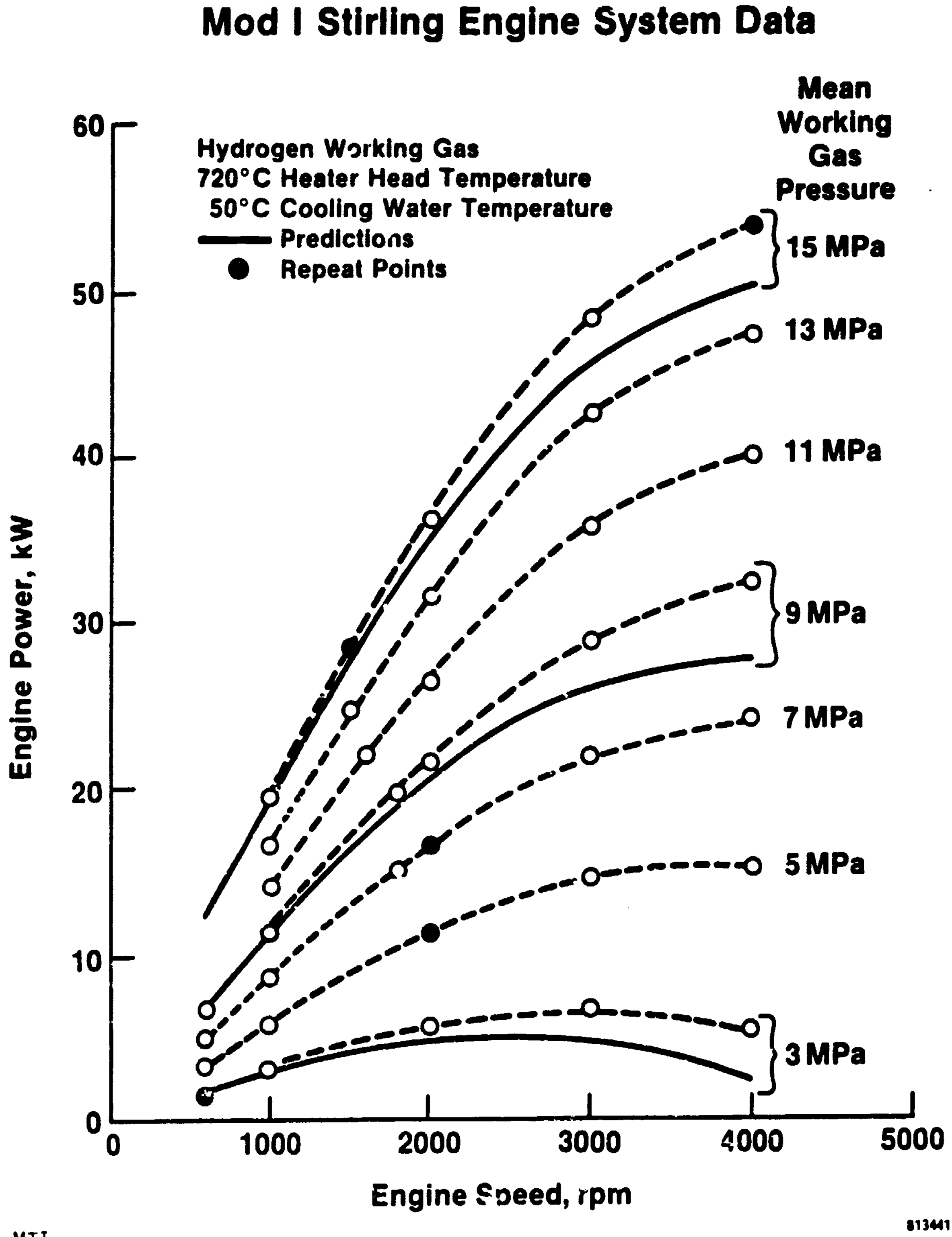

OURCE: MTI

Figure 6.3 PART LOAD ENGINE EFFICIENCY CHARACTERISTICS

Mod I Stirling Engine System Data

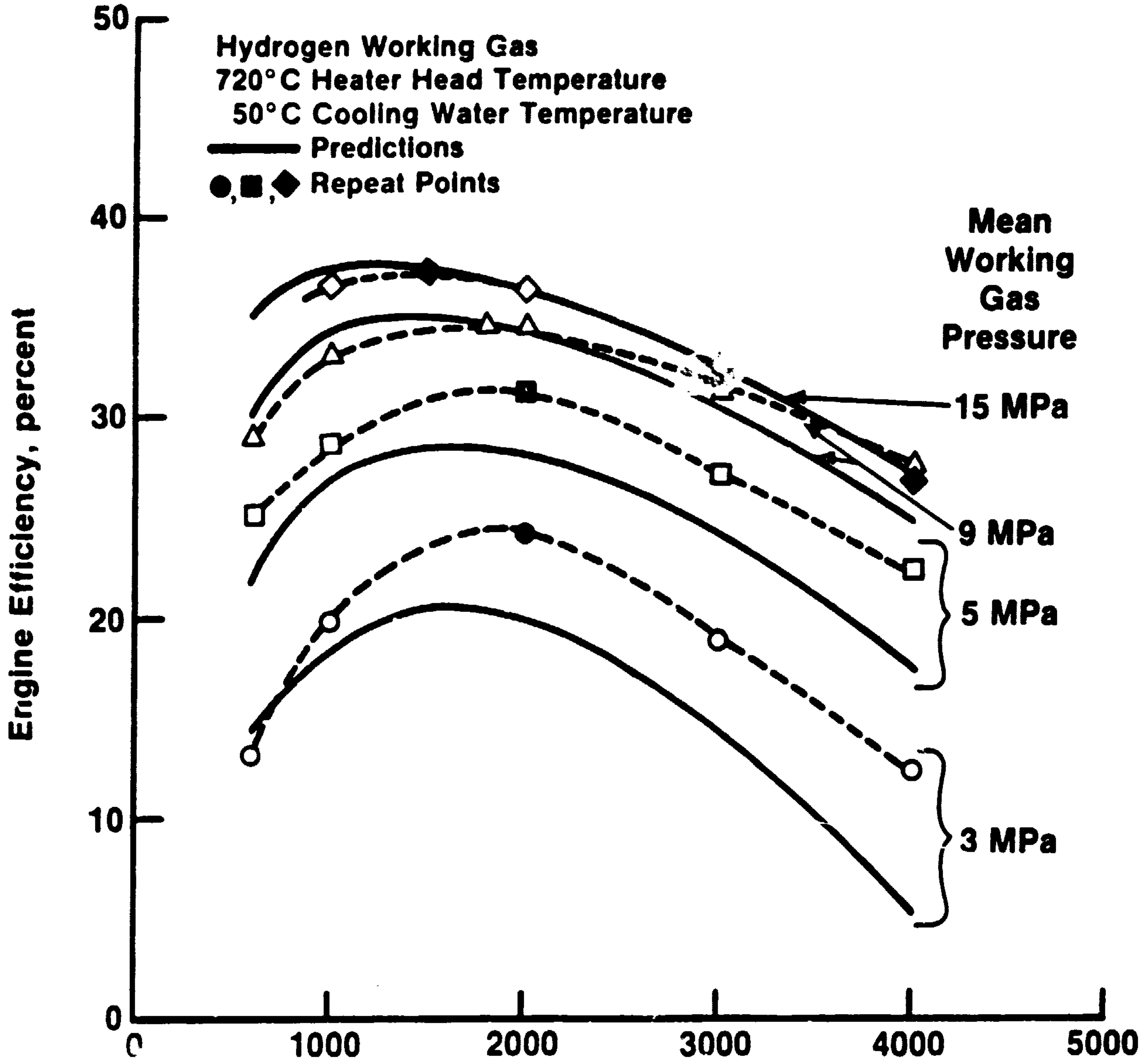

Figure 6.3 (Continued) PART LOAD ENGINE EFFICIENCY CHARACTERISTICS

However, Stirling engines require a relatively large and complex external combustion system which is not required by an I.C. engine.

This combustion system includes the blower, heater head heat exchanger, air preheater system, insulation and associated controls. As suggested by Figure 6.1, the combustion system is a major factor in determining engine size and weight.

In addition, almost all the waste heat (85%) in a Stirling engine must be rejected through a radiator (in air cooled systems) as compared to only about 60% in an I.C. engine.[9] Further, Stirling engine performance is more sensitive to cooling temperature than the I.C. engine. Thus, radiator sizes must be correspondingly larger.

The addition of heat pipe systems in connection with the heater head design is not likely to decrease the volume, since at some point the volume will be limited by that surface area needed to input the required amount of heat to operate the engine based on the heat transfer coefficients on the flame side in the combustor system. The heat pipe might, however, allow a different configuration which could allow the engine to be designed in such a way to more effectively utilize the space available. There are a number of drive configurations which if successful could improve the specific power output for the Stirling engine. However, at this stage these are still design programs with no working prototypes on which to base accurate estimates of engine size.

One of the major focusses of the automotive program has been to adapt the 4-95 designs to result in engines of acceptable size and weight for automotive applications. This program has been successful in that the MOD-I style engine* has been installed in the engine compartment of an American Motors automobile. It should be noted, however, that this engine is still larger

* The MOD-I designation refers to the first of two engine design steps in the development of the Automotive Stirling Engine (ASE). The MOD-II will be the second step, incorporating the lessons learned in the development of the MOD-I. The Reference Engine System Design (RESD) is a continuously updated paper design engine, incorporating the latest design modifications, to reflect the most advanced ASE technology at that time.

and heavier than an I.C. engine of similar capability. Basic MOD-I engine system weight is about 420 lb[19] as compared to 330 lb for a 4 cylinder L4 Internal Combustion engine.[20] Including ancilliaries (such as battery, radiator, exhaust, etc.) it appears a 3000 pound vehicle powered by the MOD I Stirling engine will be 200-300 pounds heavier than the same vehice powered by a conventional engine.[20] Later modifications may reduce the weight of the basic engine, but it is difficult to project a total engine system weight of less than that of a conventional I.C. engine.

It should be noted that the incremental size and weight of Stirling engines relative to conventional engines appears to be relatively modest and will not, in itself, be a major barrier for Stirling engine use in most of the applications under consideration.

System Cost:

A number of general studies have been performed in an attempt to quantify the cost of Stirling engine systems when produced in quantities sufficient for automotive use. They were conducted by both automobile manufacturers, and independent companies that conventionally do costing analysis for the automobile industry. All studies seem to agree that the automotive Stirling engine would be 25-100% more expensive than the same size internal combustion engine currently considered for automotive use, assuming the same production rates and power outputs.

Therefore, most developers of Stirling engines have assumed that they would be premium cost engines and that this premium would be justified by their superior efficiency, emission, multi-fuel, and noise characteristics. The primary reason for the assumed incremental cost of Stirling engines (as compared to I.C. engines) is their requirement for an efficient high temperature combustion/heat transfer system, larger radiator requirements, and possibly more complex controls. Unfortunately, there has been relatively limited detailed cost estimation of Stirling engines. The most up-to-date study was undertaken by Pioneer Engineering in support of the automotive program.[19] This study indicated that an RESD Stirling engine would cost in 1984 roughly $1815 when produced in large numbers

(300,000) as compared to a cost of $940 for a gasoline internal combustion engine including emission and catalytic equipment. A major goal of the NASA ASE Program is engine cost reduction and design improvements (discussed in Section 9) should narrow this difference. However, some premium for the Stirling engine is likely to remain for the previously discussed reasons. Other studies on automotive[21] and stationary power[22] have also assumed a cost differential for Stirling engines as compared to the most likely alternatives.

It should be noted, however, that in many stationary applications (total energy, generator sets, et .) the I.C. engines often cost well in excess of $100-200 per kW (4-8 times that of automotive engines). This is due to a need for some combination of longer life, extensive sound silencing, and emission controls, which generally lead to more expensive construction and engine derating. Stirling engines used in these applications may not carry a significant cost premium as compared to the most likely competition.

Life and Maintenance:

The Stirling engine has good potential for low maintenance. The lubricating oil is not in contact at any time with combustion products, therefore eliminating one of the major maintenance items. There are no valves or complex, precise injection, or ignition systems to need maintenance. Potential reliability problems unusual to the Stirling engine include unlubricated piston seals, rod seals, the heater head, and the gas compressor systems, in engines that use that method of power control. Overhaul items include bearings, rings, seals, and heater heads in the kinematic systems.

For the same reasons outlined above that Stirling engines have good potential for low maintenance operation, they have good potential for long life. However, this potential is as yet undemonstrated in kinematic engines. Although free piston engines have operated continuously for a significant period of time (on the order of 500 hours), very little long term, total life testing has been performed on either design. This is probably due to the fact that the application for which the Stirling engine is currently being considered most intensively is the automotive application, which has a relatively short life requirement. In a number of development programs the engine itself is used as a component development system, therefore failure of any one individual component amongst many will cause termination of the test but not necessarily from that component which is being developed. The main impediment to long life indicated so far in Stirling engine development programs is heater head design and seal life for both piston seals and rod seals.

Most engines built to date have been experimental in nature and, therefore, life and maintenance data is still quite limited. Although selected individual engines have been operated in excess of 5000 hours,[23] engine operation has generally been accompanied by numerous shutdowns where various components (seals, heaters, etc.) were changed. Table 6.3 provides information on the testing experience with the series of 4-95 test engines leading to the MOD-I designs. As indicated, typical testing times on any given unit are typically in the tens of hours range.

As indicated above, there are several reasons why more reliable operation has not been achieved and none, in themselves, appear to be unsolvable using identifiable technology. A study of automotive-derived Stirling engines for stationary applications identified design modifications that might allow a 50,000 hour life at reduced power, while still maintaining good engine efficiency.[18] Nevertheless, long-term, reliable operation is one of the few potential attributes of a Stirling engine which has not yet been satisfactorily demonstrated.

6.3 Free Piston Engines:

The evolution of free piston Stirling engines started with the work of Dr. William Beale at the University of Ohio in about 1962. This early work resulted in small scale prototype engines (fractional horsepower) which demonstrated basic operating principles of this form of engine. The potential advantages of this type of engine became more widely recognized in the early 1970's. This resulted in larger companies taking an interest in its development primarily for heat pump and solar applications, which were and still are of great interest to the gas industry and the DOE. As indicated on Figure 6.1, this resulted in free piston Stirling engine programs being initiated at General Electric and Mechanical Technology, Inc. (MTI) in the 1972-75 time period based in large part on Beale's technology developments.

Table 6.3

SUMMARY OF ACCUMULATED OPERATION TIME FOR ASE ENGINES AND MEAN OPERATING TIME TO FAILURE

ENGINE	OPERATION TIME	MEAN OPERATING TIME TO FAILURE (hrs)*
ASE 40-1 (NASA)	238.0	6.43
ASE 40-7 (MTI)	206.0	7.95
ASE 40-8 (Spirit)	292.44	3.75
ASE 40-12 (Concord)	140.4	14.04
ASE 40-4 (USSw)	6134.46	91.56
ASE 58-1 (USSw)	172.06	15.64

* All classes of failures, since initial start of the engine, are included in the calculation of mean time to failure. This includes, for example, replacement of components due t residual core particles in engine due to improper cleaning, burner blower belt failure, cracked spark plug, etc.

SOURCE: NASA/Lewis ASE Program, Reference 24.

As a practical matter, therefore, free piston Stirling engines have only been investigated for commercial applications over the last 8 years and total expenditures have been on the order of $10 million - a very modest amount for a new engine development program. The status of this technology should be viewed taking into consideration the limited resources devoted to its development.

Free piston Stirling engines either have demonstrated or could readily demonstrate many of the major operational advantages which have been verified on kinematic engines, namely:

- o High efficiency,
- o Low emissions,
- o Low noise and vibration, and
- o Multi Fuel Capability

In fact, at low power levels (1-10 kW), free piston Stirling engines may have a higher efficiency than their kinematic counterparts, since there are no mechanical shaft seal losses. The lack of a mechanical drive train could well make the free piston machinery even quieter than kinematic equipment.

The above attributes have been reasonably well demonstrated on equipment tested at SUNPOWER, General Electric and MTI. However, the cummulative operating time on free piston engines in a size range of practical interest is still less than 5000 hours with the longest operation of a single engine being about 500 hours. This longer term operation has been accomplished both at SUNPOWER on a 1 kW electric machine and at G.E. on a 3 kW Stirling/linear compressor device for integration into a heat pump systems using a conventional vapor compression cycle.

Clearly, despite the superficial simplicity of a free piston Stirling engine, there are still difficulties in transforming this simplicity into mechanically reliable hardware.

The scope of this chf this chapter do not include the very low power output (5 watt) Stirling engine heart pumps developed at the University of Washington. It should be noted, however, that this program has demonstrated that a free piston configuration using a hydraulic output system can achieve very reliable operation (35,000 hours).(25)

Recent studies indicate that this heart pump technology might be scaled up to larger sizes of more widespread interest.(25) The potential advantage of this configuration could include the elimination of power piston gas bearing or dry sliding seals and ease of energy extraction from the free piston motion. The hydraulic arrangement proposed, however, still has not been demonstrated in a size range of practical interest. Thus it is difficult to make judgements as to the applicability of this technology at this time.

In Section 6.2, it was indicated that the primary causes of unplanned shutdown with kinematic test engines were problems with:

- o Heater head
- o Piston seal
- o Shaft seal
- o Pressure level control (i.e., power control)
- o Miscellaneous parts and instrumentation

Although generally designed to be hermetically sealed to avoid the need for a shaft seal and contamination problems, free piston Stirling equipment still require a high temperature heater head and piston seals for their operation. As a practical matter, therefore, two of the critical design problem areas in kinematic engines are also present with free piston equipment.

There is no fundamental difference in the heater head requirements, between the kinematic and free piston designs. Therefore the comments made earlier regarding heater head design apply equally here.

As a practical matter, kinematic equipment requires sliding piston seals to limit the flow of working gas by the pistons. Since these seals must operate unlubricated, they have been and remain a source of concern in achieving long term operation.

With free piston equipment, two approaches are being pursued; sliding seals similar to those used in kinematic equipment and clearance seals. The sliding seals in free piston equipment are subjected to a similar environment as in kinematic equipment and, therefore, success in developing long lived seals would be generally applicable to both kinds of equipment.

Clearance seals are now used in free piston equipment (refrigeration cycles) developed for aircraft and space use. They have the advantage of resulting in no contacting surfaces and, therefore, engines using such seals should achieve long life operation.

The lack of a shaft seal on a free piston engine is a significant reliability advantage. However, to date this advantage has been somewhat counteracted by problems in the complexities associated with extracting power from a free piston machine. With linear alternators, the side forces (perpendicular to the stroke motion) generated by non-perfect geometry and windings, etc. can create loads that can cause large wear rates in sliding bearings. Clearance bearings are not quite as affected by this problem, but are correspondingly more costly and difficult to make, as well as sensitive to operate. The linear compressor design, as configured in the G.E. heat pump system, adds another degree of freedom to the control of the system, as well as another piece of moving equipment.

As a result of the above factors, the reasons for shutdown in free piston equipment has to a great extent paralleled that of kinematic equipment in:

- Heater heads
- Piston seals (sliding or clearance)
- Mechanical or electric power tranducer failures
- Miscellaneous instrumentation.

Due to the limited amount of operational experience, there is not a statistical breakdown of these shutdown modes.

The major ongoing free piston engine development programs are shown on Figure 6.1. The programs of SUNPOWER, Inc. (Dr. Beale) are privately funded and directed at heat pump and gas liquification applications. The gas liquification systems use a Stirling-Stirling cycle so that the power output of the engine does not have to be converted into electric or mechanical power. Although this provides some definite design simplicities, the issues associated with heater head and piston sealing (sliding seals) remain. The primary differences between the G.E. and MTI systems are in the piston sealing arrangement (G.E. uses sliding seals and MTI a clearance seal) and in the means of transferring power to the heat pump cycle. The limited operating experience with any of the free piston arrangements complicates the task at this time of judging which technical approaches are most likely to be successful.

6.4 Operational Issues

As indicated in the previous section, Stirling engines have demonstrated most of the favorable operational characteristics which have been promoted by their developers over the last 20 years. Even where characterisitcs such as weight, size, and cost may put Stirling engines at a disadvantage compared to alternative engines, the differentials may not be so large as to eliminate the Stirling engine from consideration. However, the life and reliability of Stirling engines has still not be demonstarated at levels sufficient to justify commercial development.

A review of the operational experience with Stirling engines indicates that the following factors have contributed to the lack of reliable operation.

High Temperature Operation:

In order to operate at high efficiency, Stirling engines require an efficient, high, temperature, combustion/heat transfer system.

Typical operating temperatures must be in excess of 1300°F, and overall combustion system efficiencies of 85% are normally required which, in turn, imply preheaters with an effectiveness in excess of 90%. Heater head designs must be consistent with both the need to achieve high combustion gas to engine working gas heat transfer rates and to minimize engine void volumes. These somewhat conflicting requirements have led to complex heater head designs.

Seals:

There are basically two types of seals used in the kinematic Stirling engine piston seals, and shaft seals, as described below.

The piston seal generally take the form of a series of piston rings that keep the working gas from passing the piston rather than going through the cooler, regenerator, and heater circuit. These rings must operate without lubrication in a relatively warm part of the engine. Leakage past these seals results in reduced engine performance and although they don't seal the entire working pressure of the engine from the atmosphere, they have been a source of considerable design difficulty. Typical seal materials used to date have been engineering plastics such as Teflon, Rulon, etc.

The shaft seal performs two functions:

- o Sealing the high pressure gas (up to 2000 psi and above) inside the engine, and
- o Preventing the lubricating oil contained in the crankcase for the drive train from entering the engine and fouling the heater head, piston seals, regenerator, etc.

The two approaches tested most to date are the Roll Sock seal of Philips and the sliding shaft seal used by United Stirling (the Leningrader pumping seal). Neither type has reliably demonstrated the length of life required in heat pump, stationary power generation, or other long life application.

It is important even in the automotive application that the goals for seal life be reliably achievable since, in present configurations, these seals are not easily replaced as in a routine maintenance procedure.

As indicated above, two approaches to piston seals are being developed for free piston Stirling engines in the size range of this study: sliding and clearance or gas gap seals.

Seals in free piston engines are not required to seal against the same pressures as in a double acting kinematic engine, due to fundamental differences in the configuration of the engines. However, the life requirements are similar as can be the temperature of operation. Additionally, changes in sliding seal friction due to seating or wearing-in of the seal can have a more pronounced affect of the performance of free piston engines than of kinematic engines, due to its sensitivity to slight changes in phase-angle between pistons.

There are basically two types of clearance seals under investigation: hydrodynamic and hydrostatic. In the hydrodynamic bearing, gas is drawn into the gap or clearance by the viscous forces of the gas and the relative motion of the parts. This type has the advantage of not using any high pressure bleed gas and therefore having the potential for low leakage losses past the bearing.

However, to result in acceptably low gas leakage rates the gap between the pistons and cylinders must be on the order of .0001" which implies machining tolerances of 0.00001". It has not yet been demonstrated that such precision equipment can be made consistent with the cost constraints of consumer products. Test engines using clearance seals have been operated for periods of up to 10,000 hours and preliminary results suggest that the technical performance of the seals appear to be attractive, if practical cost and thermal distortion issues can be resolved.[27]

Hydrostatic bearings work by supplying gas under pressure to the bearing surfaces, whether or not the surfaces are in motion relative to one another. Tolerances can be at least an order of magnitude less stringent than with the hydrodynamic seals, but the losses associated with the use of the pressurized gas can become large, if the clearance gap is excessive. Clearance gaps of 0.001-0.003 in are currently under test in free piston Stirling engine systems and, based on initial test results, appear to be operating satisfactorily.*

* From personal communications with MTI personnel.

Controls:

Present kinematic Stirling engines use variable working gas storage volume, compressor sensors, and check valves to implement. In parallel with the pressure control system, the combustion system operation must be controlled (variable blower speeds, fuel inputs, etc.) so as to maintain constant temperature operation at all loads.

These relatively complex control arrangements require the simultaneous operation of many sensors and components which can often be difficult to achieve for extended periods in test systems.

A variable angle swashplate drive system may provide a simpler, more compact and reliable method for power control of a kinematic Stirling engine. Power control is achieved by varying piston stroke. An engine using such a variable angle swashplate--the Philips Advenco Stirling engine--is currently under test at Lewis Research Center. Other expected advantages for this power control method are an improvement in part load efficiency and a faster response to torque load variations.

7.0 SELECTION OF APPLICATION CLASSES FOR STIRLING ENGINES

7.1 Comparative Engine Characteristics and Ranking of Stirling Engine Applications

This section describes the ranking of the Stirling engine application classes that were outlined in Section 4.0, for two different stages in the development of Stirling engines; current technology and developed technology.

There are a number of desirable charactristics that an engine would have when operating in any one application that could be used to describe the operation of that engine. The following is a list of these characteristics that are important to a large number of applications. Each of these characteristics is defined in Section 7.1.3:

- o Fuel Flexibility
- o Low Emissions
- o High Efficiency
- o Low Noise and Vibration
- o Straightforward Heat Recovery Potential
- o Low Maintenance
- o Long Life
- o Easy Startability
- o Low Cost
- o Low Weight
- o Small Size
- o Good Load Following (Control)

7.1.1 Relative Rankine of Stirling Engine Applications - Current Technology

Figure 7.1 summarizes the ranking of the applications identified in Section 4.0 for Stirling engines at their current stage of development. For this ranking, state-of-the-art engine technology was used as a baseline.

The top row in each category is the weight. This is the importance of that particular attribute (such as low emissions or low cost) to the application.

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Application		Fuel Switching	Emissions	Fuel Efficiency	Noise & Vibration	Heat Recovery	Maintenance	Long Life	Startability	Low Engine Cost	Low Engine Weight	Small Engine Size	Load Following	Totals	Ratio Rating	"Spread"
Total Energy/ Heat Pump		7	8	9	9	10	8	9	8	6	2	5	4	85		-.094
	C	2/14	7/56	6/54	4/36	6/60	6/48	7/63	7/56	6/36	6/12	6/30	8/32	497	5.847	
	S	9/63	7/56	7/63	8/72	8/80	2/16	1/9	7/56	3/8	4/8	4/20	7/28	489	5.753	
Industrial Equipment		5	8	6	5	0	5	7	7	6	2	5	8	64		-1.032
	C	2/10	7/56	6/36	7/35	-/0	6/30	7/49	7/49	6/36	7/14	7/35	9/72	422	6.594	
	S	8/40	7/56	7/42	9/45	-/0	2/10	1/7	7/49	4/24	5/10	5/25	6/48	356	5.562	
Powered Isotope		0	0	9	9	0	-	10	10	0	6	6	8	58		+1.052
	C	-	-	3/27	10/90	-	-	10/100	10/100	-/0	2/12	4/24	2/16	369	6.362	
	S	-/0	-/0	8/72	8/72	-/0	-/0	9/90	10/100	-/0	4/24	4/24	6/48	430	7.414	
Remote, Multi-fuel Power		9	2	6	5	4	6	7	8	6	5	5	6	69		-.015
	C	2/18	2/4	3/18	4/20	2/8	6/36	5/35	7/56	8/48	8/40	8/40	7/42	365	5.290	
	S	9/81	6/12	5/30	8/40	8/32	2/12	1/7	7/56	4/24	4/20	4/20	5/30	364	5.275	
Low Usage Equipment		4	3	3	5	0	5	2	8	10	8	7	5	60		-2.217
	C	1/4	3/9	3/9	4/20	-	7/35	7/14	7/56	9/90	9/72	8/56	7/35	400	6.667	
	S	9/36	6/18	5/15	8/40	-/0	2/10	1/2	7/56	2/20	3/24	3/21	5/25	267	4.45	
Military/Quiet Power		8	3	7	9	1	7	7	9	4	7	7	8	77		-.715
	C	6/48	4/12	4/28	6/54	3/3	6/42	6/42	7/63	6/24	8/56	8/56	7/56	484	6.286	
	S	9/72	7/21	7/49	8/72	8/8	2/14	1/7	7/63	3/12	4/28	5/35	6/48	429	5.571	
Mobile Power (Light Duty)		7	9	8	8	5	6	5	7	8	7	8	8	86		-.977
	C	4/28	7/63	7/56	7/56	7/35	6/36	6/30	7/49	8/64	7/49	7/56	9/72	594	6.907	
	S	9/63	7/63	7/56	9/72	7/35	2/12	1/5	7/49	4/32	5/35	5/40	6/48	510	5.930	
Mobile Power (Medium Duty)		7	8	8	7	4	7	8	7	4	4	5	8	77		-.753
	C	4/28	4/32	7/56	4/28	7/28	8/56	8/64	8/56	7/28	7/28	7/35	9/72	511	6.636	
	S	9/63	7/56	7/56	9/63	7/28	2/14	1/8	8/56	2/16	5/20	5/25	6/48	453	5.883	
Solar Thermal		5	0	9	7	5	8	9	8	8	7	7	7	80		-1.126
	C	7/35	-/0	5/45	8/56	8/40	6/48	8/72	7/56	4/32	5/35	5/35	7/49	503	6.288	
	S	6/30	-/0	7/63	8/56	8/40	2/16	1/9	8/64	2/16	5/35	5/35	7/56	413	5.162	
Large Stationary Power		8	8	9	7	3	7	9	5	4	2	2	8	72		-.945
	C	4/32	6/48	8/72	5/35	7/21	7/49	9/81	7/35	6/24	5/10	5/10	8/64	481	6.681	
	S	9/72	7/56	7/63	8/56	6/18	2/14	1/9	7/35	5/20	4/8	4/6	7/56	413	5.736	

Figure 7.1 STIRLING AND CONVENTIONAL ENGINE/APPLICATION ASSESSMENT – CURRENT TECHNOLOGY

The second row is the assessment of conventional engine technology to that application. The upper left hand number is the raw score given that engine and the lower right hand number is the weighted score. The third row is the assessment of Stirling engine technology to that application. The upper left hand number is the raw score given that engine and the lower right hand number is the weighted score.

For both the conventional and Stirling engine technologies the score is based on the engine that is best suited or is currently being used in that application. The performance of these engines assumes the "high quality" end of currently available technology for conventional engines and the state of current development for the Stirling engine.

The column labeled totals includes the sum of the weights (row 1) and the sum of the weighted scores, in rows 2 and 3, for conventional engines and Stirling engines, respectively. The column labeled Engine Score is the sum of the weighted scores divided by the sum of the weights for conventional engines and Stirling engines in rows 2 and 3, respectively. The column labeled classification spread is the difference between the Stirling engine score and the conventional engine score. An example of the scoring methodology is shown in Figure 7.2. The greater this number, the better the Stirling engine looks relative to a conventional engine. Figure 7.3 illustrates this rating for each application.

The ranking process requires making numerous judgements as to the relative performance characteristics of both internal combustion and Stirling engines. Making these judgements is complicated by the relatively limited operational experience with Stirling engines. The judgements made relative to conventional engine technologies are consistent with the characteristics listed in Table 5.2 for representative engines in each category. This ranking process is useful in highlighting major issues affecting the potential use of Stirling engines. However, due to the highly judgemental nature of individual entries to the ranking process, undue importance should not be attached to modest numerical difference in total scores.

As indicated, at the current state of development, only space power shows promise for being a favorable application. This is due, in part, to the fact

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HEAT PUMP/TOTAL ENERGY APPLICATION CLASS

Engine Criteria	Relative Importance of the Criteria to the Class (RI)[1]	Stirling Engine Score (SS)[2]	(RI)(SS)	Conventional Engine Score (CS)[2]	(RI)(CS)
Fuel Switching	7	9	63	2	14
Emissions	8	8	64	7	56
Fuel Efficiency	9	8	72	6	54
Noise & Vibration	9	8	72	4	36
Heat Recovery	10	8	80	6	60
Maintenance Interval	8	8	64	6	48
Long Life	9	7	63	7	63
Startability	8	7	56	7	56
Low Engine Cost	6	4	24	6	36
Low Engine Weight	2	5	10	6	12
Small Engine Size	5	5	25	6	30
Load Following	4	8	32	8	32
	Σ (RI) = 85		$\overline{SS} = \Sigma$ (RI)(SS) = 625		$\overline{CS} = \Sigma$ (RI)(CS) = 497

Classification Spread = Difference Between Weighted Averages of $\overline{SS}$ and $\overline{CS}$

$$= \frac{\Sigma (RI)(SS)}{\Sigma (RI)} - \frac{\Sigma (RI)(CS)}{\Sigma (RI)} = \frac{625}{85} - \frac{497}{85} = 1.506$$

1. Importance Criteria (1-10): Importance of the criteria to the specific application class, weighted on a scale of 1 to 10.
2. Engine Ratings (1-10): Capability of the engines of meeting the criteria, assessed on a basis of 1 to 10.

Figure 7.2 EXAMPLE OF SCORING METHODOLOGY HEAT PUMP/TOTAL ENERGY APPLICATION CLASS

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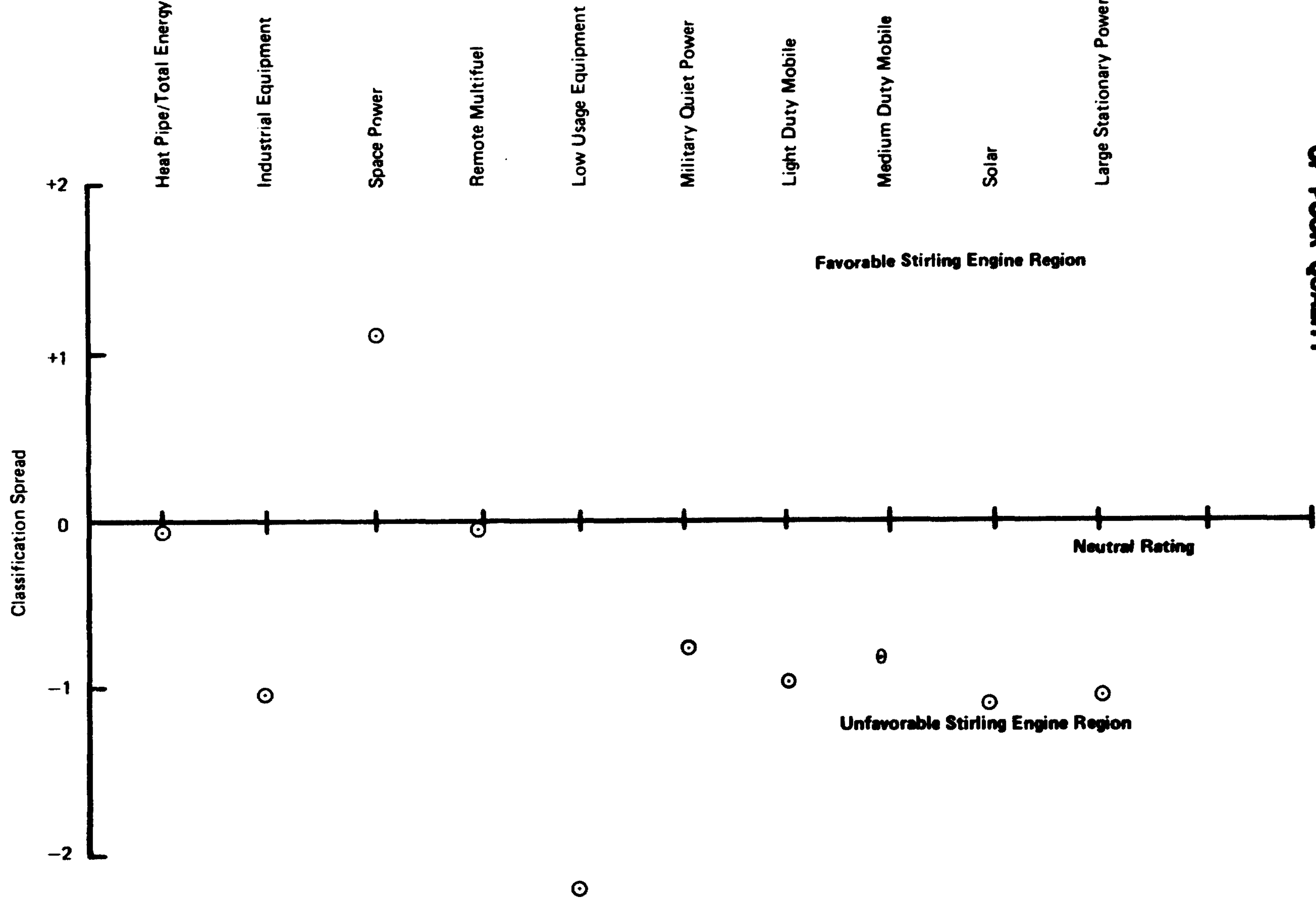


FIGURE 7-3 **RELATIVE RANKING OF STIRLING ENGINE APPLICATIONS – CURRENT TECHNOLOGY**

that high precision hydrodynamic piston seals/bearing for space free piston equipment (for refrigeration) has demonstrated long life in steady state operation typical of space applications.[27] All other applications are shown as not favorable due, in large part, to a lack of demonstrated life and reliability with equipment suitable for terrestrial applications.

7.1.2 Relative Ranking of Stirling Engine Applications - Developed Technology

Perhaps a more important exercise is the assessement of the potential of future, more developed Stirling engines that meet reliability and life goals of the various application classes. However, in the ranking it is still assumed that Stirling engines do not compare favorably with internal combustion engines relative to cost, weight, and size due to factors discussed in Section 6.

Figure 7.4 summarizes the ranking process, assuming a more developed Stirling engine technology. No changes are assumed for conventional engine technology from Figure 7.1, since the time period for developments in this area are long, relative to those in the comparatively undeveloped Stirling engine field.

As summarized in Figure 7.5, there is a rather wide range in the potential for Stirling engines in the different application classes. For purposes of this discussion the applications were divided into three categories.

(a) Not Promising

o Low Usage Equipment

Application is not dependant on the attributes of the Stirling engine for success. Depends heavily on factors such as cost, size, and weight in which the Stirling engine does not fair well, and has very stiff competition from conventional engine alternatives.

Application		Fuel Sensitivity	Emissions	Fuel Efficiency	Noise & Vibration	Heat Recovery	Maintenance	Long Life	Startability	Low Engine Cost	Low Engine Weight	Small Engine Size	Load Following			Totals	Engine Score	Ratio Rating / Commercialization Speed
Total Energy/ Heat Pump		7	8	8	8	10	8	9	8	6	2	8	4		88			1.588
	C	2/14	7/56	8/64	4/36	8/80	8/48	7/63	7/56	8/48	6/12	8/64	8/32		487		5.847	
	S	8/80	8/64	9/72	9/72	8/80	8/64	7/63	7/56	4/24	8/16	8/36	8/32		688		7.280	
Industrial Equipment		8	8	6	5	0	5	7	7	6	2	8	8		84			.780
	C	2/16	7/56	6/36	7/35	·/0	6/30	7/49	7/49	6/36	7/14	7/56	9/72		488		5.804	
	S	6/48	8/64	8/48	8/40	·/0	8/40	8/56	7/49	5/30	6/12	6/30	7/56		470		7.344	
Space Power		0	0	9	8	0	·	10	10	0	6	6	8		88			1.348
	C	·/	·/	3/27	10/80	·/	·/	10/100	10/100	·/0	2/12	4/24	2/16		405		6.882	
	S	·/	·/	9/81	9/72	·/	·/	9/90	10/100	·/0	4/24	4/24	7/56		447		7.707	
Remote, Multi-fuel Power		9	2	6	5	4	6	7	8	6	5	5	6		69			1.710
	C	2/18	2/4	3/18	4/20	2/8	6/36	5/35	7/56	8/48	8/40	8/40	7/42		365		5.280	
	S	9/81	6/12	6/36	8/40	8/32	8/48	8/56	7/56	6/36	5/25	5/25	6/36		480		7.880	
Low Usage Equipment		4	3	3	5	0	5	2	8	10	8	7	5		69			.894
	C	1/4	3/9	3/9	4/20	·/	7/35	7/14	7/56	8/80	9/72	8/56	7/35		486		6.887	
	S	9/36	6/18	6/18	8/40	·/	7/35	7/14	7/56	4/40	4/32	4/28	6/30		347		5.783	
Military Direct Power		8	3	7	8	1	7	7	9	4	7	7	8		77			.844
	C	6/48	4/12	4/28	8/64	3/3	6/42	6/42	7/63	6/24	8/56	8/56	7/56		494		6.288	
	S	9/72	8/24	8/56	9/72	6/6	8/56	7/49	7/63	4/16	8/56	6/42	7/56		540		7.130	
Mobile Power (Light Duty)		7	9	8	8	5	6	6	7	8	7	8	8		88			.888
	C	4/28	7/63	7/56	7/56	7/35	6/36	5/30	7/49	8/64	7/49	7/56	9/72		584		6.807	
	S	9/63	8/72	9/72	9/72	7/35	8/48	8/30	7/49	6/48	6/42	6/48	9/72		661		7.570	
Mobile Power (Medium Duty)		7	8	8	7	4	7	8	7	4	4	8	8		77			1.088
	C	4/28	4/32	7/56	4/28	7/28	8/56	8/64	8/56	7/28	7/28	7/56	9/72		511		6.636	
	S	9/63	8/64	8/64	9/63	7/28	8/56	8/64	8/56	5/20	6/24	6/40	7/56		588		7.636	
Solar Thermal		5	0	9	7	8	8	9	8	8	7	7	7		80			1.212
	C	7/35	·/0	5/45	8/56	8/80	6/48	8/72	7/56	4/32	5/35	5/35	7/49		503		6.288	
	S	6/30	·/0	8/72	8/56	5/40	8/64	8/72	8/64	6/48	7/49	7/49	8/56		600		7.500	
Large Stationary Power		8	8	9	7	3	7	9	8	4	2	2	8		72			1.041
	C	4/32	6/48	8/72	5/35	7/21	7/49	9/81	7/56	6/24	5/10	5/10	8/64		481		6.681	
	S	9/72	8/64	8/72	8/56	6/18	8/56	9/81	7/56	5/20	5/10	4/8	8/64		556		7.722	

Figure 7.4 STIRLING AND CONVENTIONAL ENGINE/APPLICATION ASSESSMENT - DEVELOPED TECHNOLOGY

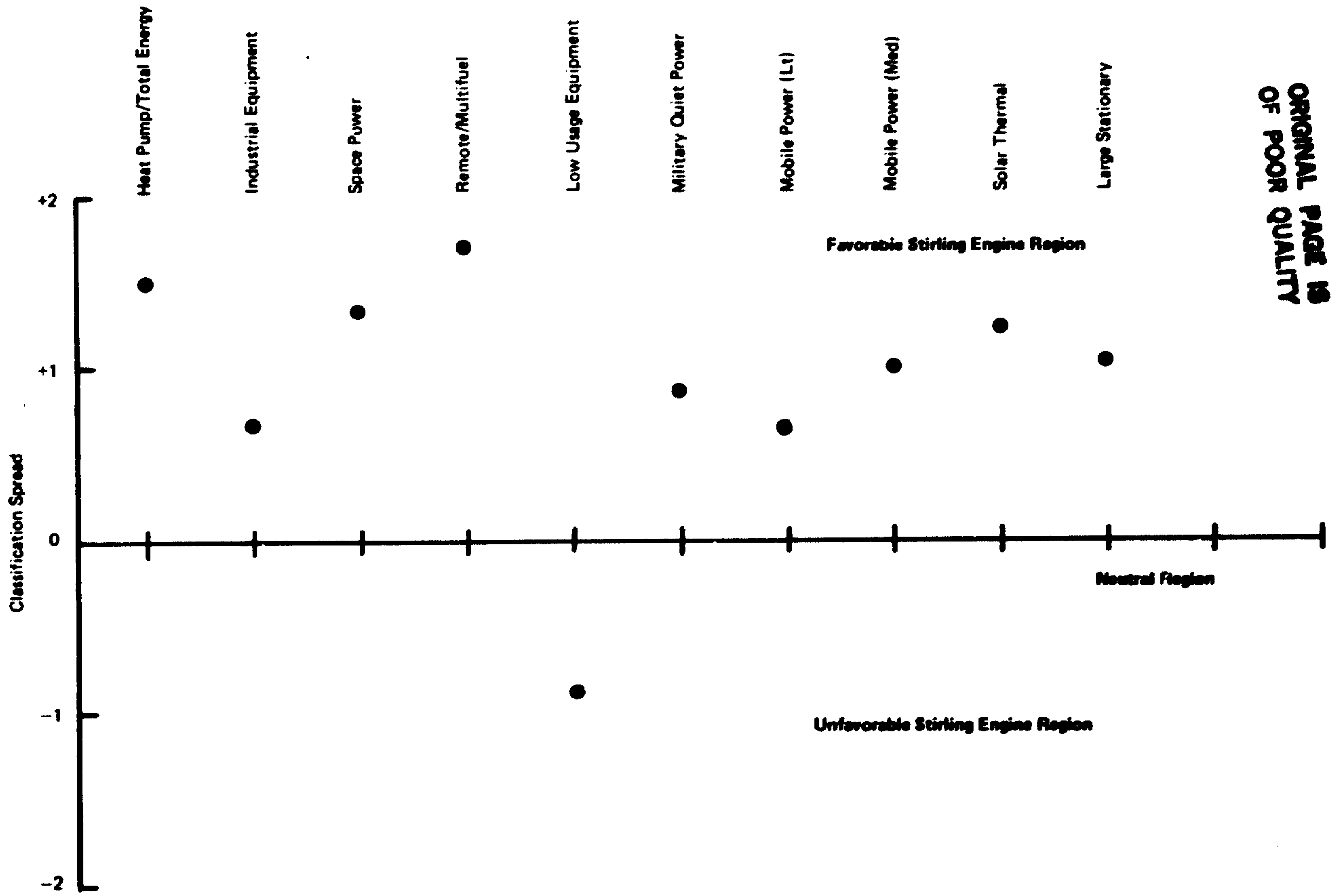


Figure 7.5 **RELATIVE RANKING OF STIRLING ENGINE APPLICATIONS – DEVELOPED TECHNOLOGY**

(b) Intermediate

In these applications the potential advantage of Stirling engines, even in their developed state, appear to be modest as compared to more conventional alternatives. However, in applications with very large market potentials, these modest advantages could still have significant total impacts.

- Light Duty Mobile

Competition from conventional engine technology (Diesel and Otto cycle engines) is extremely keen, with both types receiving intensive development effort from public and private sources. Cost, size, and weight restrictions are severe, and there is significant infrastructure for conventional engine technology already in place. However, the potentially large market and impact of these engines warrants continued parallel development of the technology.

- Industrial Equipment

There is a relatively small market which is reasonably well served by conventional alternatives, although positive attributes of Stirling engines are potentially important in these applications.

- Military Quiet Power

Also a relatively small market with difficult (and expensive and time consuming) certification procedures (military specs) and control requirements. However, cost not so critical and advantages of Stirling engines are important in this application.

(c) Promising

- Heat Pump/Total Energy

Has a large potential market, and few competitive engines. Attributes of Stirling engine technology are critical in this application and cost, weight, and size requirements are not as critical.

- Space Power

Although a small market, in terms of number of units sold, potential attributes of free piston Stirling engines are very important, and cost is not an important factor. Competition is not as well-suited to larger power sizes as Stirling engine.

- Remote Multifuel

Competition is not currently serving this market adequately (primarily using inexpensive gasoline engines and small Diesels), since none are multifuel. Cost, size, and weight constraints are not critical. Market is large particularly in remote areas of developing countries. There is also potential for significant domestic market, in remote areas or in second or vacation homes away from the power lines.

- Medium Duty Mobile Power

Although competition is tough, cost, size, and weight constraints are less than with light duty mobile power and Stirling engine attributes are important in this operation.

- Solar

Large potential market competition is from Rankine cycle and Brayton engines, as well as photovoltaics. Stirling engine attributes such as efficiency are important in this application although cost and low maintenance are important constraints.

- Large Stationary Power

Cost, weight, and size constraints not critical. Multifuel capability desirable as are other Stirling attributes. Market relatively small, and will not likely justify development of engines specifically for this market.

7.1.3 Definition of Desirable Engine Characteristics

The following descriptions are intended to briefly outline each of the engine characteristics and the rationale behind the score of the conventional engine system. Stirling engine performance is outlined in detail in the previous section, and is not repeated below.

Fuel Flexibility:

Although difficult to quantify, fuel switching capability is desirable in a number of applications. For example, remote or military power generation, where supplies of one type of fuel might easily be interrupted, but others might still be available, would clearly benefit from being able to use solid fuels as well as a variety of more conventional gaseous or liquid fuels. Other applications such as solar thermal and low usage equipment (lawn mowers, chain saws, etc.) place less importance on fuel flexibility than other characteristics, simply because the end user doesn't see fuel flexibility as an important constraint to effective operation.

Conventional internal combustion engines, are usually not well suited to the use of radically different fuels. This is primarily because the combustion/fuel handling systems must be carefully integrated into the design of the prime mover part of the engine system. For example, in the light duty mobile power application (automotive), many engines are designed to use lead free gasoline. The use of any other fuel (with the possible exception of certain gaseous fuels) can damage or otherwise make inoperative other parts of the system, such as carburetor, valve seals, catalytic converters, etc. In the case of the Diesel engine, the diesel fuel itself provides lubrication to the fuel injection systems. The use of straight gasoline, which has very poor lubricating properties in a Diesel engine would result in substantial damage in a very short period of time. Thus, conventional (I.C.) engines do not score well in fuel flexibility. Gas turbine and Rankine cycle engines can be somewhat better, depending on design.

The Stirling engine, on the other hand, being an external combustion engine, can have a more independent combustion/heat transport system. Tests and demonstration systems built to date have demonstrated the ability to operate on a wide variety of fuels, including liquid and gaseous fuels as well as various solid fuels, such as cattle dung, rice husks, wood chips, etc. Thus, the Stirling engine is rated well in fuel flexibility.

Emissions:

The emissions characteristics of an engine can be an important issue on both a national/social scale, as in the case of the automotive and heat pump applications, and an individual basis, as in the case of industrial equipment. The Environmental Protection Agency (EPA) of the United States Government has mandated a series of emission standards for automobiles sold in the United States. These standards have had a serious impact on the design of engines for automotive use. (Similar standards are being considered for home heating systems.)

For engines used in less open spaces such as mining vehicles or fork lift trucks, the effects of that particular engine on the operator of the equipment is of greater importance than the aggregate effect of those engines on society as a whole.

For other applications, such as remote or military power, low usage equipment, etc., the engines may be small in output, far from populated areas, or used relatively infrequently, and for these applications emissions is not a crucial area of consideration for the user.

The difficulty in achieving a low emission, I.C. engine stems from the fact that the combustion process takes place within the engine cylinders, under difficult to control, time and load varying conditions. In an effort to alleviate the atmospheric pollution problems of many urban areas, conventional I.C. engine has had considerable development in the past 10-12 years, including after process cleanup (catalytic converters, EGR, etc.), improved air/fuel control, advanced ignition systems, turbocharging, etc. Current technology I.C. engines, particularly for automotive use, can operate with good exhaust emission characteristics and are rated fairly well in those applications.

The Stirling engine with its external combustion system can operate with low emissions in almost any application, and is rated highly on this characteristic.

Efficiency:

Efficiency is clearly an attribute that is desirable in any application. In some cases, such as space power and solar thermal, the efficiency of the engine has a direct impact on the "fuel source" requirements. For example, a more efficient engine could require less solar collector or a smaller nuclear or isotope heat source as well as a smaller heat rejection system. For larger stationary power, heat pumps, and light and medium duty mobile power, an efficiency at least equal to that of conventional engines currently used will be required to achieve some penetration of the current market for that equipment. In some applications, fuel efficiency is not as critical a factor, such as in low usage equipment, or military quiet power generation, where other factors such as weight, cost, or low noise are more important than the last few percentage points in efficiency.

As covered in Section 5.0, conventional engine efficiencies range from 10-15% for single cylinder, low cost Briggs and Stratton type engines, to 18-25% for gasoline automotive engines as well as gas tubines on up to 30-40% for large, low speed Diesel engines and Rankine cycles. Conventional engine efficiency is well-documented, and can be quite high. For this reason, the conventional engine can be rated reasonably high within any given application class.

As previously mentioned, the Stirling engine can operate very efficiently in a range of sizes and is therefore scored very well, usually incrementally higher than I.C. engine alternatives.

Noise and Vibration:

Although noise and vibration may, in some applications, be tolerable, it is never desirable. Noise is critical in certain applications such as military power where quiet operation is necessary to avoid detection and heat pump systems where use in residential areas will prohibit the operation of noisy engine systems. In other applications, vibration is critical; for example, in space systems, vibration could be potentially damaging to sensitive electronic components. Similarly, vibration in a solar collector system could hamper long term performance of the system. Low noise and low vibration levels are also important in light and medium mobile power applications.

Conventional gasoline internal combustion engines can be made to be quiet and smooth by design, muffling, special mountings, enclosures, etc. The Diesel, by nature of the combustion process it utilizes, is a noisier, more vibration prone engine. Gas turbines can be very smooth engines but are generally quite loud unless extensive muffling to the intake and exhaust is performed. Rankine cycles are also reasonably quiet and smooth.

The Stirling engine has the potential to be quieter still, due to the lack of valves and continuous combustion process. Therefore it is rated very highly in this category.

Heat Recovery:

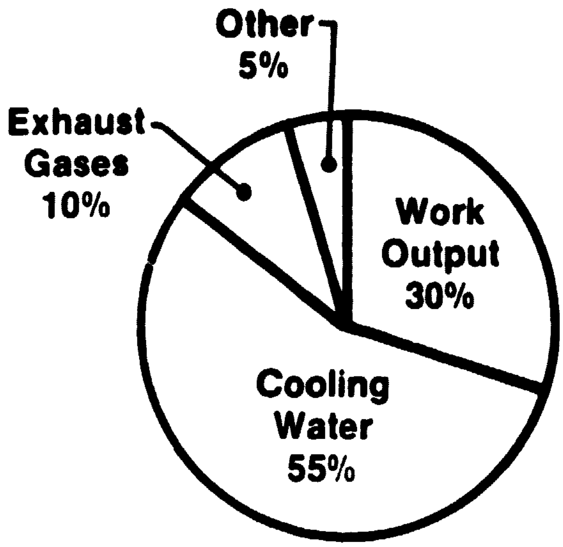
There are two aspects to heat recovery. The positive is that the heat can be utilized in an associated or separate application at no detriment to system operation. The negative (heat rejection) is that this heat must be removed from the engine for continued operation. This can result in extra components for the engine as well as efficiency penalties for certain types of engines. Heat recovery is critical to the economic application of heat pumps and total energy systems. It can be important in solar thermal applications, large stationary power, and mobil power application. Heat recovery is of little or no consequence in space power, industrial equipment, and low usage equipment, although heat rejections is necessary in all of them. A great many internal combustion diesel and Otto cycle engines are liquid cooled. For these engines, heat recovery can take place in three areas: a) the cooling jacket, (b) exhaust gases, and c) lubrication systems. For gas turbine systems energy recovery is primarily from exhaust gases. For air cooled engines, heat is only available from the exhaust and lubrication systems. For a Rankine cycle engine, heat is potentially available from a cooling or heat rejection system and the combustion system.

For internal combustion engines, relatively high temperatures are available with very little effect on engine performance. However, to recover this energy requires the addition of an additional heat exchanger in the exhaust stream. This component can be expensive and must be carefully designed and installed to avoid degrading system performance. Figure 7.6 illustrates the apportionment of heat from the various sources for an internal combustion engine and a Stirling engine. Some care must be taken in recovering heat from the exhaust stream to avoid condensing water vapor from the exhaust and creating a c rrosive environment in various engine components. Conventional engines are ratea moderately for heat recovery.

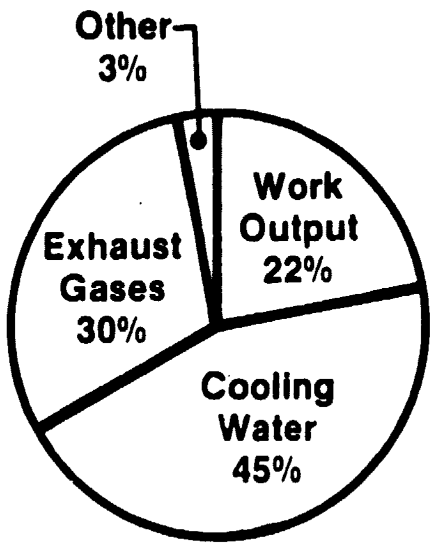
The Stirling engine is different in that the major source of heat is from the cooler. A small amount of heat is also available from the combustor after passing through the air preheater. Thus, it is easier to collect the majority of reject energy from a Stirling engine, since it comes mostly from the cooler, which each engine must have. The disadvantage with heat recovery in the Stirling engine is that since the efficiency is inversely proptional to the cooling temperature it is desirable to extract heat from the engine at as low a temperature as possible, thus in some cases reducing the usefulness of the collected heat. Stirling engines are therefore rated well on heat recovery, since no additional equipment is needed, and most of the heat can be recovered.

Maintenance:

Maintenance requirements can be described in terms of level of skill required to perform that maintenance (such as simple oil change or ignition system maintenance, on up to overhaul) and the frequency of that maintenance. whether it be scheduled or unscheduled, due to some form of breakdown. Maintenance can be important from two standpoints. One is economic, whether the burden of the expense of doing the maintenance is prohibitive in a certain application. The second is from a logistics standpoint, i.e., the difficulty of obtaining maintenance and/or parts. Maintenance is critical in space power applications from a logistics viewpoint. It is of primary importance in military systems, from a logistics standpoint and in heat pump applications, stationary power applications, solar, and medium mobil applications from an economic standpoint. Maintenance is not thought to be as critical in light mobil applications, industrial applications, remote power generation, and low usage equipment.



Mod I Stirling Engine



Conventional Gasoline Engine

Figure 7.6 CONVENTIONAL AND STIRLING ENGINE ENERGY BALANCE AND ENERGY RECOVERY POTENTIAL

With conventional engine systems maintenance is often inversely proportional to the cost and often the life of the system. Small engines can need maintenance every 25 hours, amounting to oil changes, filter changes and ignition systems tune ups. On the other hand, well designed Diesel and gas turbine engines can go thousands of hours before maintenance is required.

Maintenance, as indicated above, varies from inspecting and/or replacing air and oil filters, adjusting injector and ignition systems, valves, coolant levels, on up to an overhaul which requires a major disassembly of the engine, replacement of bearings, piston rings, valves, valve guides, seats, etc. Conventional engines are rated well on maintenance, since they can be selected for the application based on that requirement.

A well developed Stirling engine should be somewhat better on maincenance and is so rated based on the factors outlined in the previous section

Life:

There are two ways of discussing the life requirements of an engine. One is in terms of absolute number of hours and the other is relative to the life of the piece of equipment in which it is installed. Thus the term long life can have a different meaning depending on the application. Similarly, life can be important from a logistic standpoint (difficulty in replacing an engine) and from an economic standpoint where the cost of replacing the engine is prohibitively expensive in a given application. Long life in terms of total number of hours operated is critical in space applications, solar, large stationary power systems, and heat pumps. Life requirements are not quite so stringent in applications such as low usage and light mobil power applications where as long as the engine lasts the life of the rest of the equipment it will be satisfactory (500-3000 hrs).

Life before overhaul of a conventional Diesel and Otto cycle internal combustion engine can be from 1,000 to 50,000 hours. 1000 hours might correspond to a single cylinder Briggs and Stratton type engine, and 3,000-5,000 hours for a gasoline fired internal combustion engine for an automobile. 50,000 hours might be expected of a reciprocating Diesel in a long life type application. Gas turbines and Rankine cycle engines have been known to run for hundreds of thousands of hours before failure or need for total overhaul. Internal combustion engine failures are generally due to bearings, valves, or rings. Gas turbines have similar failure modes in bearings, as well as turbine and compressor, erosion and degredation. Thus, conventional engines are rated quite well in long life category.

Stirling engines have the potential for long life for the same reasons as they have potential for low maintenance and, therefore are rated very well.

Startability:

Conditions effecting the startability of an engine are the reliability with which the engine can be started, the ease or difficulty with which it can be started, and the time to either maintain its own idle power or develop full power. Startability is important in most applications and critical in a few such as space and military. In these applications, an engine that won't start is of very little value.

Most conventional engines need a starter motor of some type to initiate the cycle to the point where it can carry on its own loads. A typical Otto cycle engine in an automobile has a 15 second start requirement from when the key is first turned until the automobile is driven away. Diesel engines generally take somewhat longer than this to warm up the glow plugs, particularly in cold weather. Gas turbines can be slower yet, taking significant time (2-30 minutes) to reach speed to avoid compressor stall and achieve good temperature stabilization. Rankine cycles tend to be slower yet requiring time to initialize boilers, condensers, etc.

Conventional engines are rated quite well in startability in most applications.

As indicated in previous sections, Stirling engines should start as well as conventional engines and are rated about the same.

Engine Cost:

Engine cost can be a main driver in many applications, typically those with a mass market such as low usage equipment, light duty mobil power applications, and solar thermal applications. This is mainly based on the fact that the competitive engines such as the Briggs and Stratton and automotive type engines are so low in cost. Engine cost is less critical where other characteristics such as fuel savings or efficiency or reliability are important such as space applications, military, stationary power, or total energy heat pump systems.

It must be kept in mind that, as pointed out in previous sections, conventional engine technology is extremely well-developed. Engines of both small and medium sizes are produced in very large volumes and present very tough competition from a cost standpoint. For this reason the conventional engine is rated very well from a cost standpoint.

The Stirling engine has a number of specialized components peculiar to it (as discussed in previous sections) and therefore production costs are not expected to be as low as those for conventional engines. Thus its score is lower than that of the I.C. engine.

Small Engine Size:

In certain applications, the physical size of the engine will be a constraining factor. For example, if in light mobile power applications, the engine will not fit under the hood with all its auxiliary components, battery, condenser, and other equipment, it will not be acceptable. Small engine size is usually important but not critical in low usage equipment, military, quiet power generators, solar thermal applications and space systems. As indicated, the gas turbine and two stroke engines are the lowest followed by the Briggs and Stratton type single cylinder low power engines in turn followed by internal combustion engines of gasoline fired and Diesel fired engines on up to low speed Diesel engines and Rankine cycle engines.

The conventional engine is rated moderately on size.

As indicated previously, the Stirling engine will generally tend to be larger than a similar size conventional engine since the component required for combustion, preheating, etc. is significantly larger than the air handling equipment for the conventional engine, while the remainder of the system will be similar. Hence, the Stirling engine is rated lower than conventional engines.

Low Engine Weight:

A highpower-to-weight ratio, although desirable in any application, is truly important in only a few such as low usage equipment, military power, and solar thermal. In space applications a high power-to-weight ratio fot the total system (thermal energy source, heat transport subsystem, power converters, and radiators) is critical.

The very high efficiency of Stirling engines in such applications would tend to reduce the size and weight of the thermal source and heat rejection subsystems. This provides some additional flexibility in the design parameters for the engine itself.

Typical conventional Otto and Diesel cycle engines are generally quite heavy (10-50 Kg/kW). Such engines are often used in applications where weight is not a critical factor. Where weight does become important two stroke and gas turbine cycle engines can have very high power to weight outputs generally at some sacrifice in efficiency, pollution characteristics, or perhaps life. Rankine cycle engines generally have poor characteristics from a weight standpoint and are not generally considered for mobil type applications.

The Stirling engine is rated lower than the conventional engine alternatives for the same reasons as described in the preceding paragraphs on engine size.

Load Following/Control:

In this section load following is defined as the ease with which the engine can be controlled to follow a given load or demand placed on that engine. The following is very important in low and medium power mobil applications, military applications, industrial power, and stationary power generation. Other applications such as total energy systems, remote multi-fuel, and low usage do not demand rapid fluctuations in output from the engine to perform their functions. As indicated in the section on Emissions, rapid changes in output demanded of an engine can have significant effects on the emission characteristics for that engine and therefore, load following control is connected to the emissions characteristics of an engine.

The conventional internal combustion engine is an excellent load following device. It is well understood how throttle position, rpm, and manifold pressure are related and can be controlled almost instantaneously to adjust the output. The gas turbine can have from fair to good characteristics in power control, although in some cases it can be expensive. Rankine cycle engines often have slow response and in order to avoid poor load following characteristics require, sophisticated control systems, due to the large thermal inertia of the boiler and other heat transfer components of the system. Conventional engines are therefore rated quite well in load following.

The Stirling engine will probably have good load following characteristics, as described in previous sections. The mass of the heater head and the movement of gas into and out of the engine (in pressure control systems) will dictate a response time poorer than that of a conventional I.C. engine. Variable displacement systems (swashplate, Z drive, etc.) will likely have response times similar to I.C. engines.

7.2 Selection of Baseline Stirling Engine Systems

As indicated in the previous section, there are 9 classes of applications which show potential of being served by Stirling engines, assuming engines are developed which meet the primary goals of present development programs.

In principle, a series of engines could be developed to uniquely serve the needs of each of these application classes. This would involve the development of several dozen engine systems which is clearly impractical. Equally important, common engine designs can be developed which with minor modifications can be used to serve a multiplicity of applications. Developing a small number of baseline engine systems has the advantage of:

- o Resulting in engines which can serve a variety of potential markets, thereby reducing development risks.
- o Allowing for reduced development and manufacturing costs, since a small number of common engine designs can be produced in large quantities.
- o Addressing specialized markets with particularly favorable near-term potential with engines which can be eventually used in larger market segments.

It should be noted that the above approach for Stirling engines is not fundamentally different from that followed with conventional engines. Basically similar engines are often used to satisfy widely divergent applications. For example, automotive engines are used for irrigation pumping and, on a limited scale, for commercial scale gas fired heat pumps (in Europe only, at this time). Similarly, medium size Diesels (30-100 hp) are used for tractor drives as well as for generator sets.

The selection of baseline engines to serve the potentially favorable application classes of Figure 7.5 is a highly judgemental process. The basic goal of this process was to identify engine categories which:

- o Served a number of potentially favorable applications having common technical and cost requirements.
- o Differed from other engine categories in important characteristics so as to define a unique engine category.
- o Had market potentials spread across several favorable applications, which merit the associated development costs and risks.

Utilizing the above criteria, engine categories were identified which could address all the favorable applications of Section 7.1. These engine categories are:

- o Simple Rural Power

- Silent Power Generators
- Automotive and Automotive Derived Power Unit
- Large, High Duty Cycle, Stationary Power

The applications comprising each of these engine categories are schematically illustrated in Figures 7.7 through 7.10 and the technical requirements of an engine for these applications are shown in Tables 7.1 through 7.4. In most cases, the requirements of these applications are formulated by assessing those engines currently in use or in applications where there is no current market, determining what characteristics would be necessary for that application to find widespread use. Brief descriptions of each engine category follow.

Simple Rural Power (Multi-Fuel):

Several studies(28) point out the need for simple power systems for use in rural areas both in the United States and in developing countries. Presently, rural power needs can be served by various forms of I.C. engines. Where heavy duty cycles are involved, derated I.C. engines or Diesel engines are typically used. These engines are, however, relatively unreliable when used in rural areas with harsh operating conditions and, in some cases, minimal maintenance. Furthermore, the I.C. engines can only operate on a limited range of commercial fuels.

An important requirement of a rural Stirling engine power system is that it can operate on non-commercial fuels often found in such areas, as well as on liquid and gaseous commercial fuels. These fuels include charcoal, wood and crop residues (rice husks, etc.).

As indicated schematically in Figure 7.7, such a multi-fuel engine would have a wide range of applications, including:

- General electric power generation.
- Water pumping.
- Farm equipment.

In the United States, a simple rugged wood fired engine could find a market segment for rural second homes and camps as well as for use in farms where crop wastes are generally available. In developing countries they could

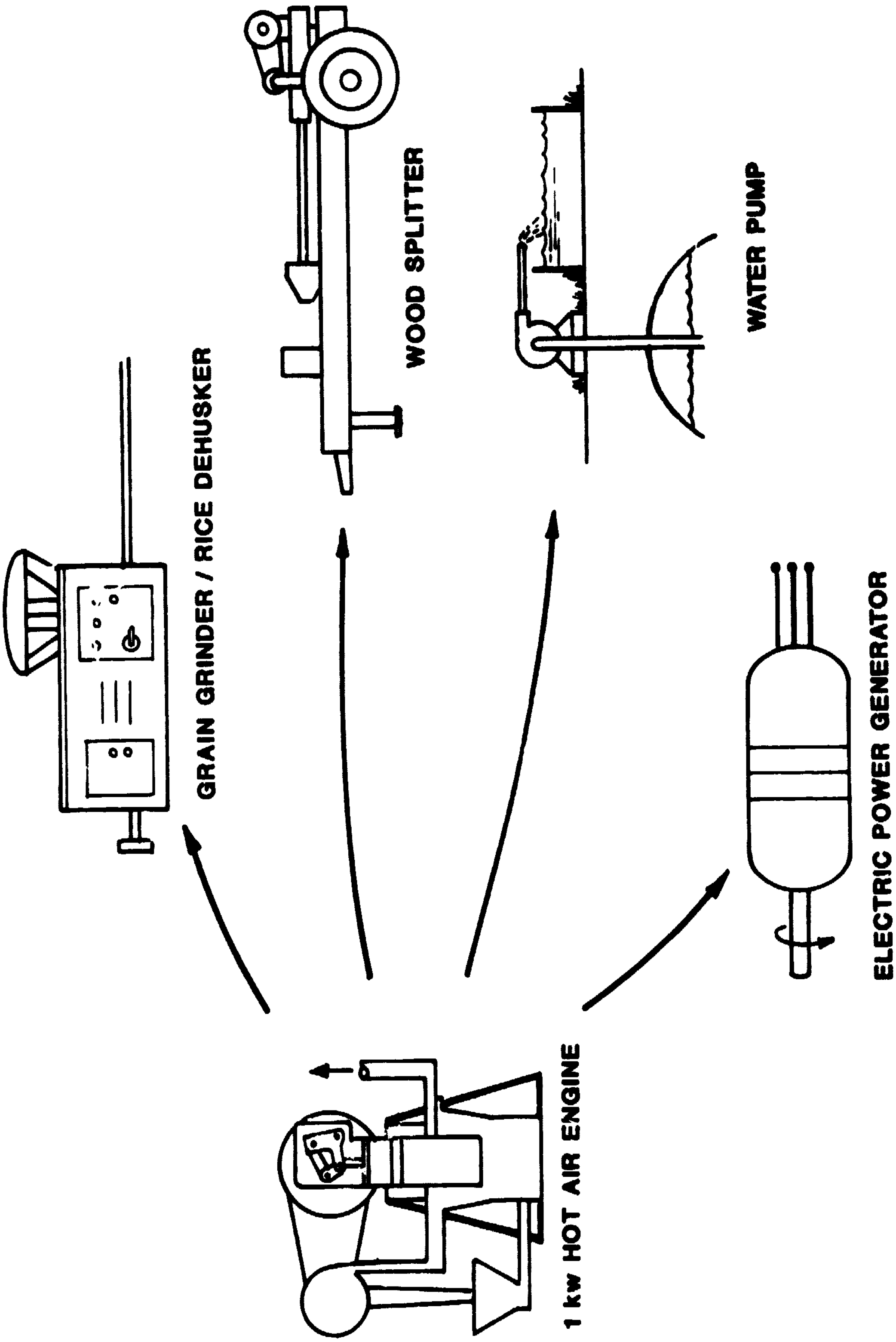


Figure 7.7 APPLICATIONS POTENTIALLY SERVED BY A SIMPLE RURAL POWER ENGINE

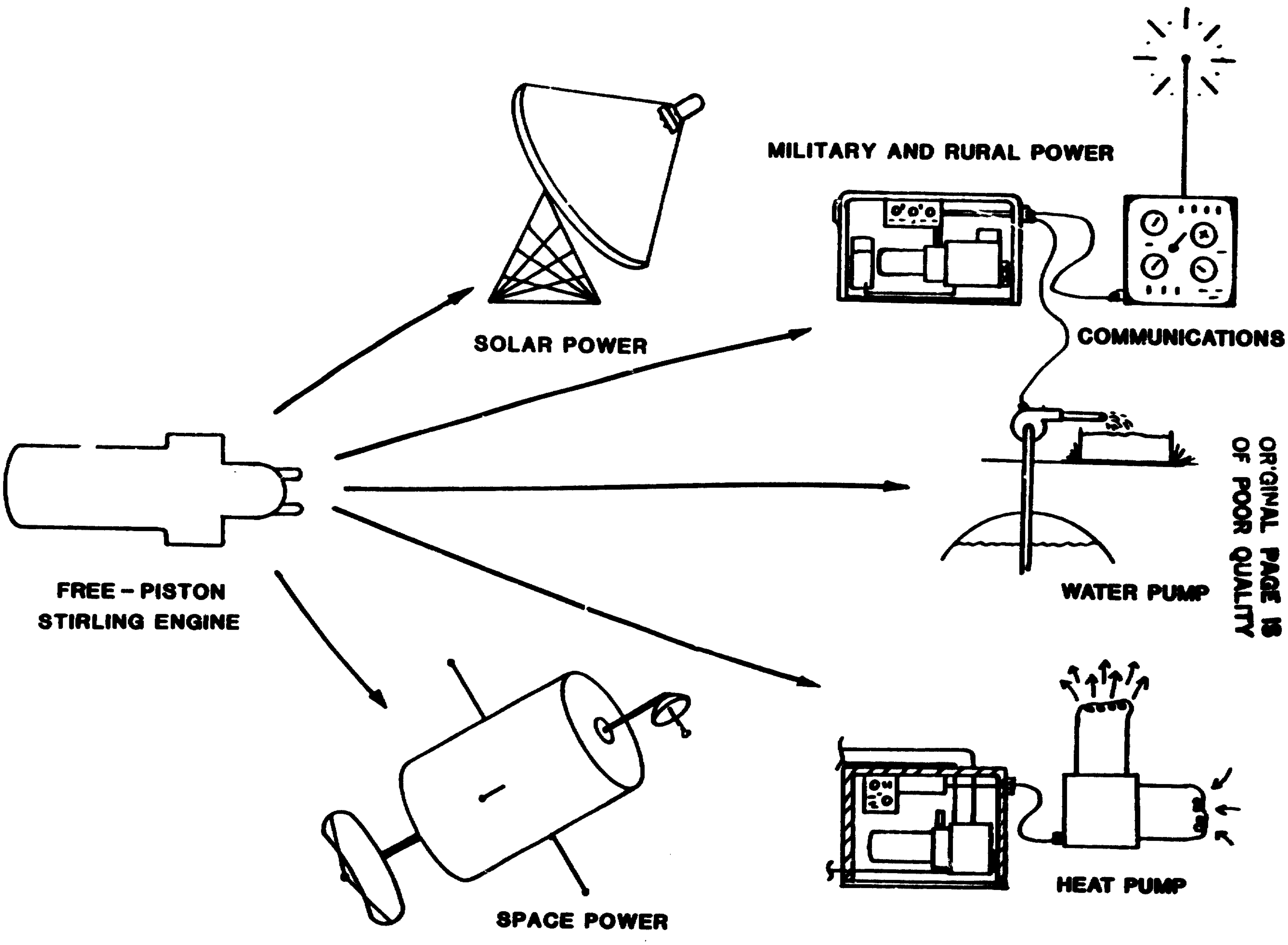


Figure 7.8 APPLICATIONS POTENTIALLY SERVED PY A SILENT POWER GENERATOR

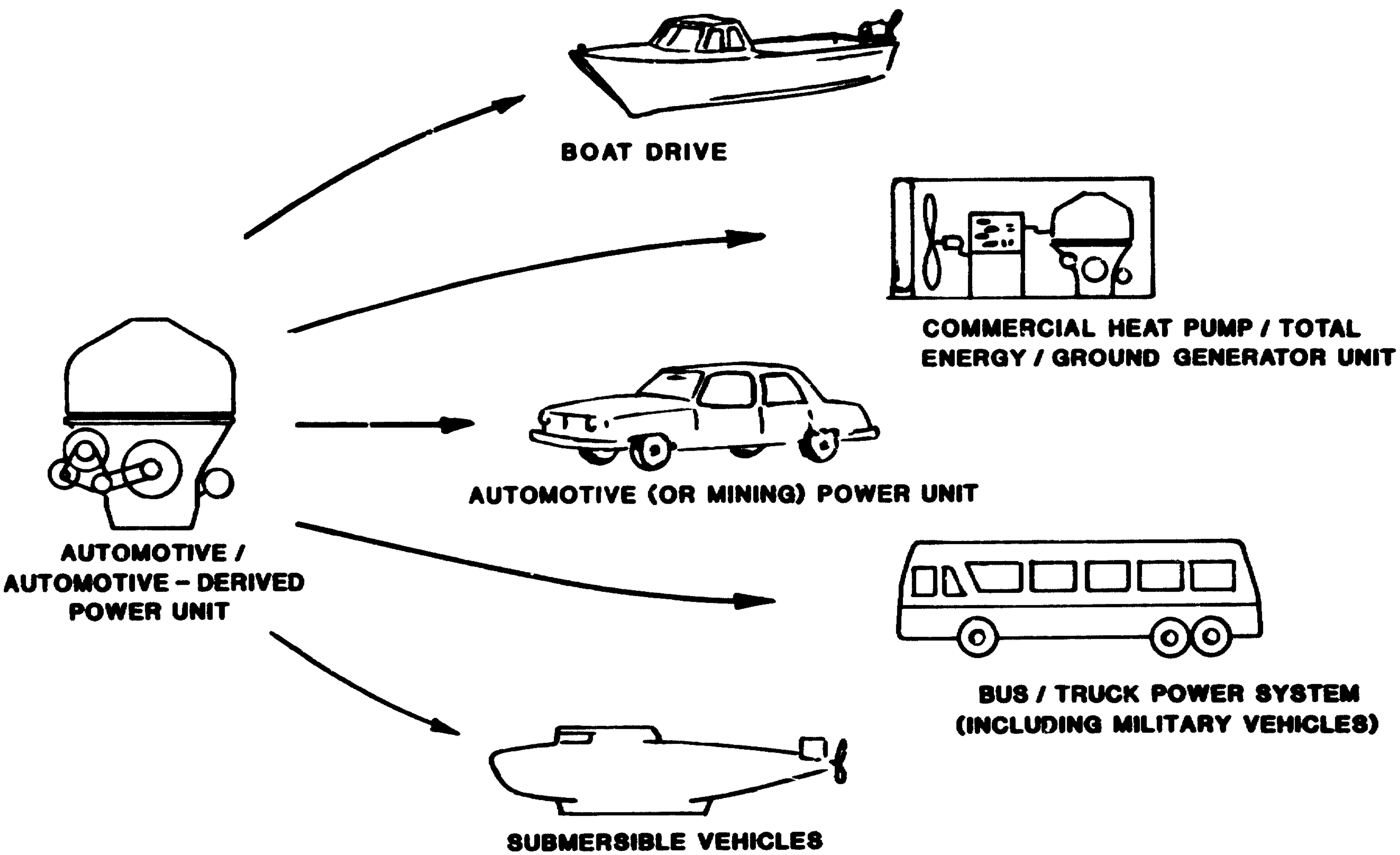


Figure 7.9 APPLICATION CLASSES POTENTIALLY SERVED BY AN AUTOMOTIVE/AUTOMOTIVE DERIVED POWER UNIT

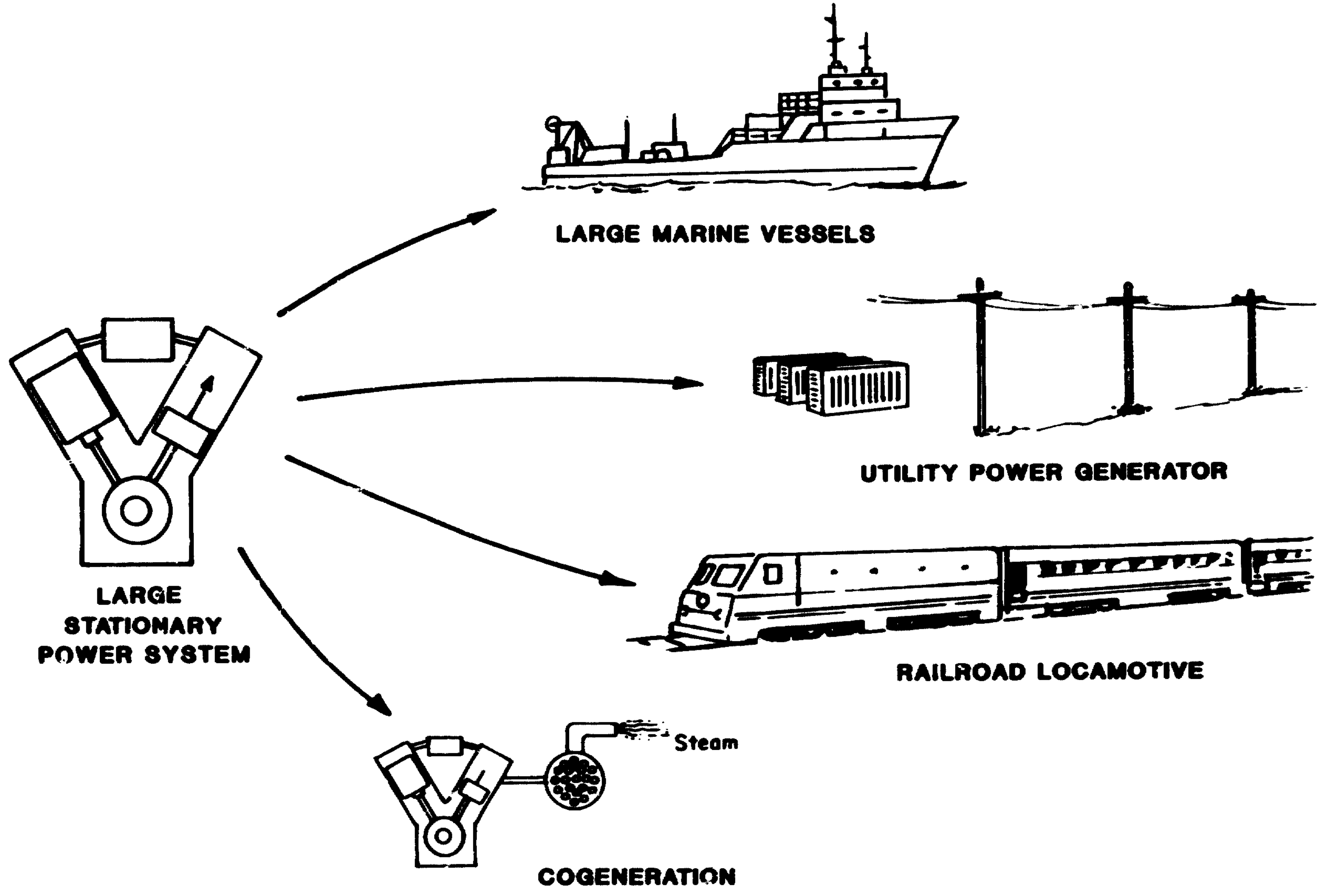


Figure 7.10 APPLICATIONS POTENTIALLY SERVED BY A LARGE, HIGH DUTY CYCLE POWER SYSTEM

TABLE 7.1

RURAL POWER SYSTEM REQUIREMENTS

Power Level	1 - 20/kW
Efficiency	10 - 20%
Emissions	Not Important
Noise Level	Not Important
Heat Recovery	Desirable but not essential
Maintenance Interval	2 - 4 Times/Year (500-1000 Hrs.)
Life Before Major Overhaul	7 - 10 Yrs. (5000 - 10,000 Hrs.)
Cost	\$200 - 400 -Operated with commercial fuels
	\$400 - 600 -Operated with Biomass fuels
Weight	30 - 60 kg/kW*
Size	.020 - .080 M^3/kg

* Based on a 50% Allowance Over Available Engines.

TABLE 7.2

SILENT POWER SYSTEM REQUIREMENTS

Power Level	3 - 30/kW
Efficiency	25 - 35%
Emissions	Application Dependent
Noise Level	Low Noise Important (Less than 65-75 dBA @ 1 Meter)*
Heat Recovery	Application Dependent
Maintenance Interval	1-2 Times/Yr (2,000 - 5,000 Hrs.)*
Life Before Major Overhaul	7-15 Yrs.- 15,000 - 25,000 Hrs.*
Cost	$250 - $500/kW
Weight	7 - 20 kg/kW
Size	.003 - .008 M^3/Hr.**

* Heat Pump Requirements Used to Quantify these Parameters - Some Applications May have Less Severe Demands

** Based on a 50% Allowance Over Available Engines

TABLE 7.3

REQUIREMENTS OF APPLICATIONS SERVED BY
AUTOMOTIVE AND AUTOMOTIVE DERIVED POWER SYSTEMS

	LIGHT DUTY (AUTO)	HEAVY DUTY (TRUCKS, ETC.)	HEAT PUMPS, ETC.
Power Level	30 - 100 kW	50 - 300 kW	30 - 100 kW
Efficiency	25 - 35%	25 - 35%	30 - 40%
Emissions	EPA Standards HC - .41, CO - 3.4 NO_x-1.0 GM/Mile Particulates - .6 GM/Mile	EPA Standards HC - .41, CO - 3.4 NO_x-1.0 GM/Mile Particulates - .6 GM/Mile	Site Specific
Noise Level	Low Noise Desirable (75-80 dBA @ 1M)	Low Noise Desirable (75-80 dBA @ 1M)	Site Specific
Heat Recovery	Application Dependent	Application Dependent	Primary Importance
Maintenance Interval	250 - 500 Hrs.	1000 - 2000 Hrs.	1 - 2 times/yr (2,000 - 5,000 hrs)
Life Before Major Overhaul	2 - 3,000 Hrs.	8000 - 12,000 Hrs.	7 - 15 years (15,000 - 25,000 hrs)
Cost	\$15 - 30/kW	\$50 - 60/kW	\$200 - 500/kW
Weight	3 - 5/kg/kW	7 - 10 kg/kW	7 - 20 kg/kW
Size	.003 - .005 M^3/kW	.006 - .009 M^3/kW	.005 - .015 m^3/kW

TABLE 7.4

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LARGE STATIONARY POWER SYSTEM REQUIREMENTS

Power Level	500 - 5000/kW
Efficiency	30 - 40%
Emissions	To Meet Local Standards
Noise Level	Application Dependent (No Federal Regulation at Present)
Heat Recovery	Application Dependent
Maintenance Interval	4,000 - 8,000 Hrs.
Life Before Major Overhaul	30,000 + Hrs.
Cost	$250 - 450/kW
Weight	Not Critical (20 - 50 kg/kW)
Size	Not Critical (.030 - .100 M^3/kW)

help provide critical power needs using locally available fuels which would ensure a strong base of support from governments and multi-lateral financial institutions (World Bank, etc.).

Table 7.1 summarizes the requirements for an engine system to be viable from technical/economic points of view in this category of applications. As indicated, only moderately high efficiencies of 10-20% will be required since conventional engines utilizing fossil fuels typically operate in this range. Emission levels are not critical nor is heat recovery. Noise levels, while not critical, must not be harmful to bystanders or operators.

Maintenance is acceptable 2 to 4 times per year, but should be performed only with basic tools and a minimum of skilled labor. Lifetime before major overhaul should be at least 5,000-20,000 hours to be competitive. Engines currently used range from small gasoline engines requiring frequent maintenance (25-50 hours) and having relatively short lives (up to 1,500 hours) up to small Diesels with infrequent maintenance (100-500 hours) and long life (up to 20,000 hours).

Acceptable costs range from $200-400/kW for engines that will be run primarily on fossil fuels, up to $400-600/kW for engines which are run on biomass. The difference is attributable to the fuel savings for the biomass operated system. Neither weight nor size are critical and could be as much as 50% greater than conventional engines.

Silent Power System:

In several of the application classes of Figure 7.4, low noise and vibration operation is one of the most important features. These applications are shown schematically in Figure 7.8 and include:

- Residential/Small Commercial Scale Total Energy/Heat Pump Systems.
- Military Generator Sets.
- Solar Thermal Power.
- Space Power.

As a practical matter, therefore, the development of highly reliable, low noise, engine systems could, in principle, address many of the most highly ranked Stirling engine applications.

At the present time, these application classes are either not being addressed at all or are addressed inadequately by existing engines. For example, I.C. engines have been used in demonstration heat pump systems but have not been widely accepted in part due to their high noise levels. Similarly, space thermal power is now generated using thermoelectrics which have very low efficiency (6%) making their use in larger power systems of the future highly problematic.

The market size for this engine category is difficult to estimate since many of the application classes it would serve are not now served by conventional engines. However, for an engine meeting requirements summarized in Section 4.0, the market should be substantial. For example, over 2 million residential size heating systems are sold annually for both new construction and replacement markets. Even a modest penetration into such a large market area could result in a significant sales potential for engine driven heat pump systems.

Table 7.2 summarizes the requirements for an engine system to be successful in this category of applications. Several studies[29] have indicated a requirement of a 30+% efficiency in heat pump applications, in order to be competitive with electric driven systems. Emission levels for fossil fuel operated systems will be very important in heat pump or total energy applications (less than or equal to a furnace in residential use), but not so critical in remote or military power use. Low noise will be important in all these applications, with the possible exception of solar power generation in remote areas.

Infrequent maintenance is important in all these applications. Maintenance at 1 to 2 times per year (or 2,000-5,000 hours) is required in most of these applications, and a life of 7-15 years (15,000-25,000 hours) is required for economic competitiveness particularly in solar thermal or total energy heat pump applications, at the engine costs outlined below. Clearly, if engine costs were lower, life would not need to be so long.

Acceptable costs based on competitive systems and application requirements range from $250-500/kW, for terrestrial applications. Size and weight, while not critical in heat pump systems (can be up to 50% over conventional alternatives) is important in space solar and military applications.

Automotive and Automotive Derived Power System:

The largest single category of engines sold today are those developed for vehicular propulsion. The large majority (95%) of these engines are used in automobiles and light trucks which clearly represent the major long-term incentive for the government to support the development of high efficiency, low emission, Stirling engine systems.

A large number (over 100,000 units/year) of automotive engines are, however, sold annually in a variety non-automotive applications such as inboard boat engines, irrigation pumps, and farm equipment.

In addition, automotive engines have been used in demonstration systems for commercial size heat pumps and total energy systems.

As indicated in previous sections, the life requirements of the automotive application are considerably shorter than for most other applications in this size range. Derating and possibly design modifications to the basic automotive engine configurations will likely be needed to address these longer life applications.[18]

As with conventional automotive engines, the automotive Stirling engine could be adapted to address a range of applications where the Stirling engine attributes are particularly important. These application classes, as indicated schematically in Figure 7.9, include

- o Heat Pump/Total Energy (commercial sizes)
- o Marine Power
- o Stationary Power
- o Mining Equipment

The commercial success of an automotive Stirling engine program does not, therefore, depend solely on the near-term implementation of the automotive Stirling engine for general purpose vehicular propulsion. The markets represented by non-automotive application could, in themselves, be substantial. Thus, an automotive Stirling engine program could lead to viable engine systems in a number of applications, perhaps before they find success in the vehicular applications.

Table 7.3 summarizes the requirements for an engine system to be successful in this category of applications. Engine costs are based on the large production volumes associated with penetration into the automotive market.

As indicated, an efficiency of 25 to 35% will be required in all these applications because current technology gasoline engines operate at 25% and Diesel engines at 35%. Emission characteristics will clearly have to meet EPA standards for the automotive application, perhaps some lesser standards for boat drives, etc., or maybe even more rigorous for commercial heat pumps/total energy systems. Heat recovery is critical to thermal applications but not important to boat drives or submersible vehicles.

Maintenance intervals, as shown in Table 7.3, as well as life, cost, weight, and size are dictated by the characteristics of current technology alternatives, namely gasoline and Diesel internal combustion engines.

Large, High Duty Cycle Stationary Power

Several studies have indicated the potential applications for a large stationary Stirling engine power plant similar to the large low speed Diesel, gas turbine, or small steam turbine power plant in application areas. The primary motivation for the development of such an engine is the ability of the Stirling engine to use a variety of fuels such as coal, refuse, etc., in addition to conventional fossil fuels. Other attributes include high efficiency, good emission characteristics, and quiet operation.

As indicated schematically in Figure 7.10, an engine of this type would find a range of applications including

- o Cogeneration
- o Pipeline Power
- o Utility Power
- o Ships and Barges

The development of such an engine would permit the generation of electricity in close proximity to noise sensitive areas such as apartment or office buildings, for use in distributed energy systems. The fuel flexibility would permit the operator to operate on whatever fuel was least expensive at the time, promising economic incentive to use this type of engine.

The market for this class of application is relatively small, less than 1,500 units sold per year in the above 500 hp size range. While the development of Stirling engine technology probably isn't justified on the basis of this application alone, scaling up an engine developed for another application might be.

Table 7.4 summarizes the requirements for an engine system in order to be successful in this category of application. Current technology Diesel engines in this size range are operating at 30-40% efficiency, although gas turbine and steam cycle can be 20-30%.

Emission levels are highly dependent on the application; for utility power generation, EPA standards must be adhered to. For ship use, there are not currently any regulations. The same applies to noise levels. Heat recovery is clearly important in cogeneration applications, but not in the remaining.

Maintenance is a crucial factor, as is long life. Maintenance intervals of 4,000 to 8,000 hours have been achieved as have total life times of 30,000+ hours with conventional engines and thus will be required of the Stirling engine.

Conventional engines in this size range cost from $250-450/kW. Size and weight are not generally crucial factors and allowances of 50% over conventional technology, as shown in Table 7.4, are probably acceptable.

7.3 Conceptual Designs for Baseline Systems

This section presents conceptual engine designs for each of the four engine categories identified in the previous section. In these conceptual designs, the engine system is defined as all those components needed to perform in a given application including cooling systems and pumps, combustors, batteries, control systems, and, in some cases, fuel tanks, not just the prime mover or mechanical part of the system.

For each application class there are a number of Stirling engine configurations which could be selected as the baseline design. For example, either free piston or kinematic Stirling engines could, in principal, be used in all application classes. In this section, the baseline engine design selections are consistent with the emphasis of current programs. For example, most current efforts directed toward silent power systems (heat pump applications, etc.) assume the use of free piston equipment. On the other hand, automotive derived engines would, of necessity, be based on kinematic engines which can be interfaced with automotive power trains.

Simple Rural Power:

As indicated in the previous section, the performance requirements (efficiency, etc.) of the simple rural power systems are not particularly stringent. On the other hand, such systems must have a rugged simple construction consistent with operation and maintenance in harsh environments.

The basic system configuration selected for this application class is a modern version of a hot air engine. Such engines cannot achieve the efficiency or power density capabilities of Stirling engines using high pressure helium or hydrogen working fluids. However, they have several potential advantages which are important for this application class.

- o Using 1-2 atmospheres of air, the power density is relatively low which results in a good thermal match with the relatively low heat fluxes provided by simple biomass combustion systems. As such, heater heads of simple design can be utilized which can be integrated with a solid fuel combustion chamber in a straightforward manner.
- o There are no critical sealing problems since only low pressure air is involved and small amounts of leakage between the working volume and the outside air have only minimal effects on performance.
- o The equipment is comprised of sheet metal, cast iron, and standard mechanical parts which do not require high tolerance manuracture and are consistent with field repair and operation.
- o Early experience with hot air engines suggests that they can achieve high reliability and can be of simple construction. It is expected that the very low efficiencies and power densities of the early engines can be greatly improved using modern technologies to increase operating temperatures, improve combustion efficiency through air preheating, utilization of regenerators (which early hot air engines did not use), and improved mechanical drives.

There is relatively little work now underway to develop hot air Stirling engines since most funded activities stress high performance applications. Figure 7.11 is a schematic of one of the few hot air engines designed using modern Stirling engine practice which is now being developed by SUNPOWER, Inc. This engine is being developed for rural power applications in developing couantries and, if successful, would provide an example of this engine category. Table 7.5 compares the demonstrated capabilities of a Stirling engine in this category (based in part on SUNPOWER's projections) to the application requirements and with the representative conventional engine capability. As indicated, the Stirling engine system would have a major advantage in having a wide fuel flexibility and can probably meet the cost requirements of this application - particularly if they can effectively use biomnass as a fuel.

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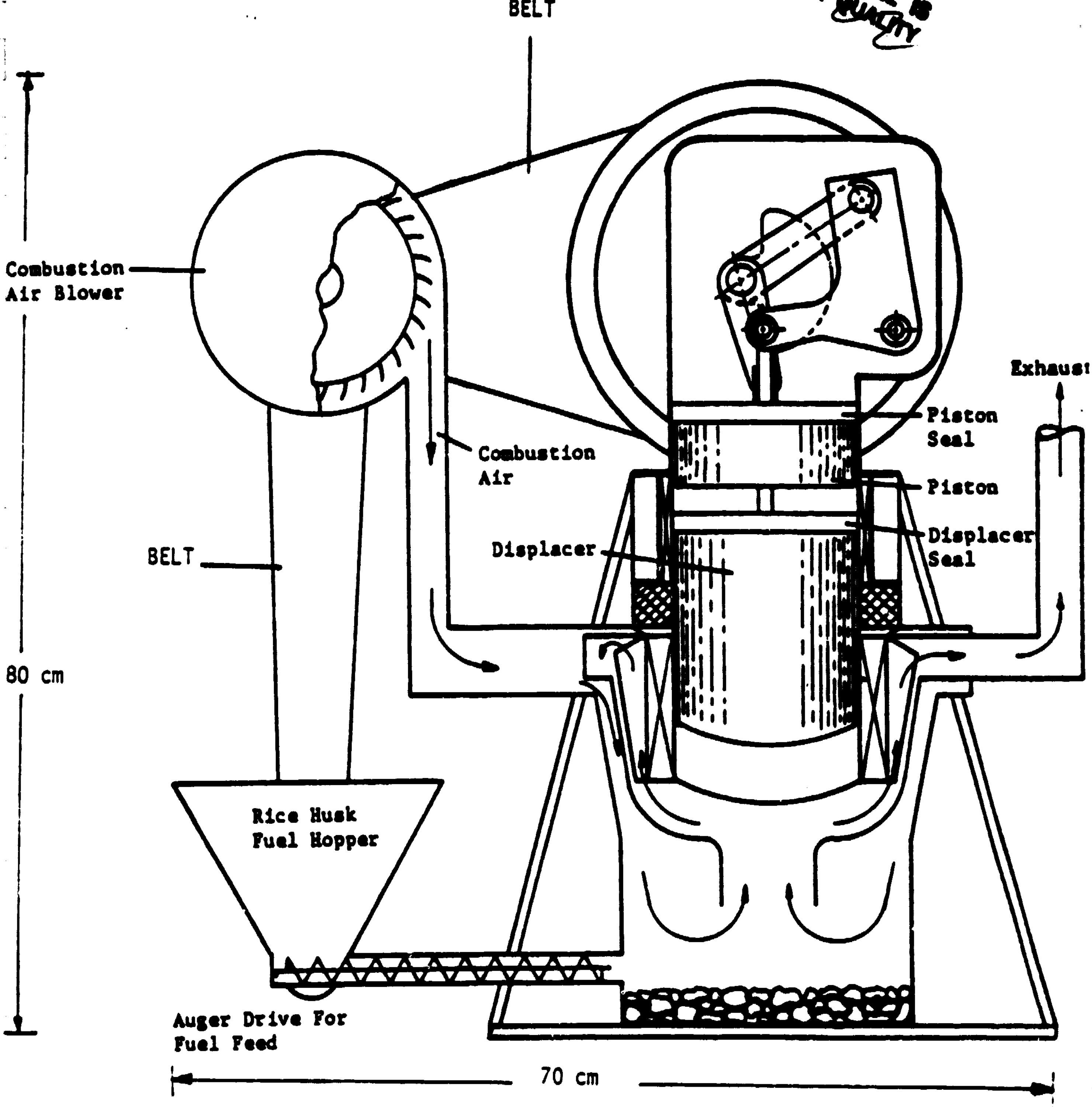

Figure 7.11 1 kW HOT AIR ENGINE SYSTEM

Table 7.5

COMPARISON OF CONCEPTUAL DESIGN WITH APPLICATION REQUIREMENTS - RURAL POWER SYSTEM

	APPLICATION CLASS REQUIREMENTS	REPRESENTATIVE[1] ENGINE CAPABILITY	STIRLING ENGINE CAPABILITY[3]
Power Level	1-100 kW	9 kW	Cover Complete Range
Efficiency	10-20%	28% (liquid fuel only)	25-30% (liquid fuel fired)
		Not Important	10-20% (Biomass fired)
Emissions	Not Important		
Noise Level	Not Important		
Heat Recovery	Desirable but not Essential	Water cooled: can recover heat from exhaust oil and coolant	Note 4
Maintenance Interval	2-4 times/year (500-1,000 hours)	~1000 hours	TBD[5]
Life Before Major Overhaul	7-10 years (5,000-10,000 hours)	~20,000 hours	TBD
Cost	\$200-400 Fossil Fuel \$400-600 Biomass	~\$300/kW No Biomass Firing Possibility	Higher end of cost range probably achievable
Weight	30-60 kg/kW	55 kg/kW	
Size	.020-.080 M^3/kg	.029 in/kg	

1. Assumed to be a Thermo King C201 with characteristics from Table 5.2.
2. Can recover heat from exhaust gases and water cooled radiator
3. Consistent with conceptual design.
4. From cooler water flow - easier than with I.C. engine.
5. Needs to be demonstrated by future program initiatives.

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Silent Power Generator:

Figure 7.12 is a conceptual illustration of a silent power generator used in a solar electric power generation application. The prime mover is a free piston Stirling engine with a linear alternator on the power piston. The engine includes the receiver, into which light is reflected from the concentrating dish, the controls mounted at the base of the dish, the heat rejection system, and the load controller, to prevent over loading the engine generator. With an appropriately designed receiver, such a system could also be operated during non-solar or partial-solar conditions on a clean fossil fuel.

Both kinematic and free piston engines are being considered to serve this application class. For purposes of the conceptual design a free piston engine configuration was assumed.

In the system shown the dish would be approximately 13 feet (4 meters) in diameter for a 3 kW peak engine and would produce 20-25 kW per day in an area with representative solar conditions. It would track the sun in 2 axes, with the engine and receiver placed at the focal point of the dish to maximize system efficiency. The dish could be constructed from a number of aluminum panels with reflective plastic coating. The electricity is conducted through the cable to the control panel/load controller.

The Stirling engine package size is influenced by the size of the heat input subassembly (combustion chamber, air preheater, heater head) and auxiliary subsystems such as the radiator and control package. As indicated in Figure 7.12, if the radiator and controls are located separately from the basic engine package, its size is consistent with solar/dish applications as well as other applications where small size is an important criteria.

Figure 7.13 is a schematic of a Stirling engine driven linear alternator arrangement based on a system under active development. If successful, this engine could meet many of the technical performance requirements of the conceptual design. The projections for this engine, a variant of that designed by MTI, are summarized in Table 7.6. As shown, this is a 3 kW output, free

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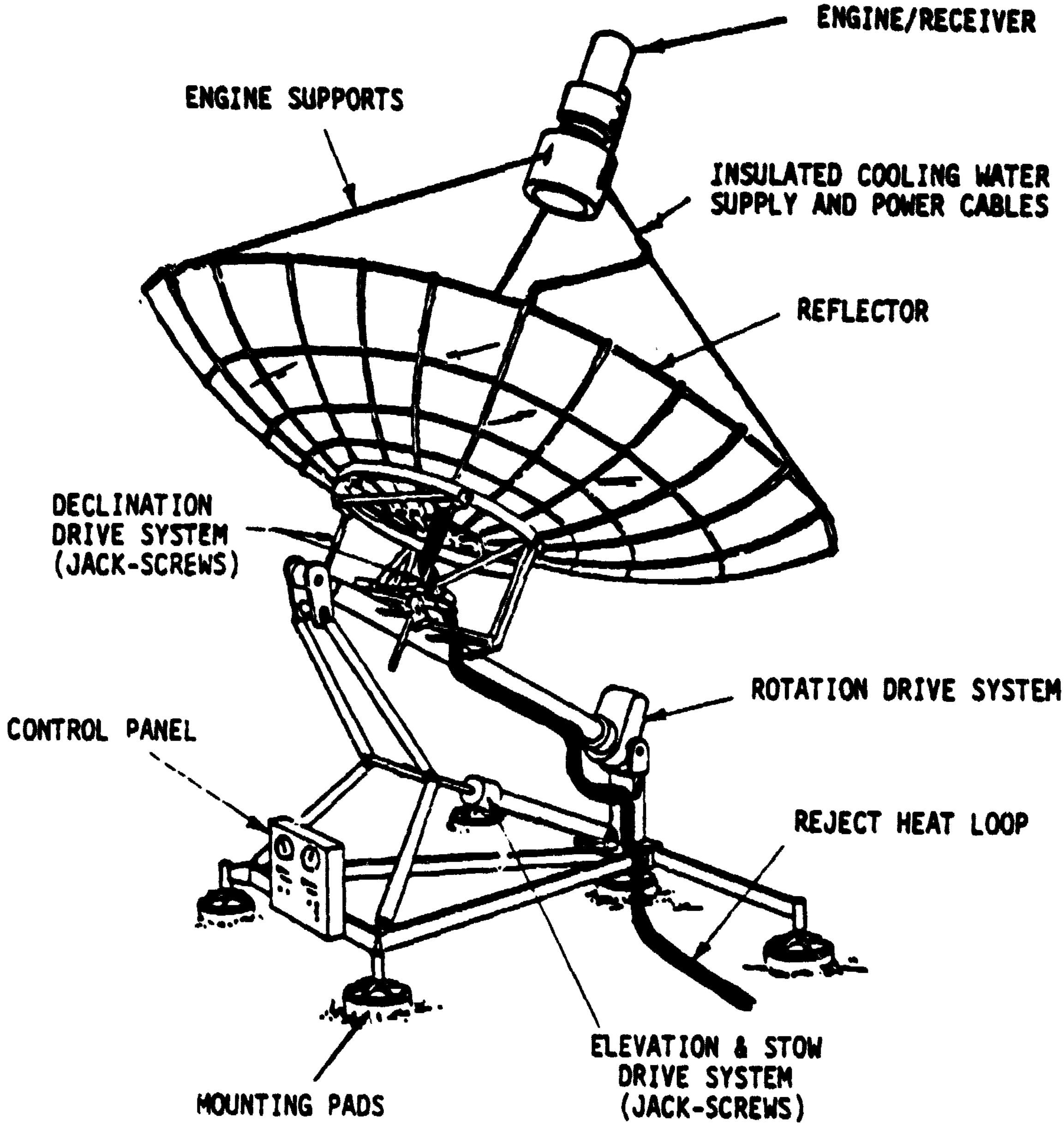

Figure 7.12 CONCEPTUAL DESIGN OF A SILENT POWER GENERATOR USED IN A SOLAR THERMAL APPLICATION

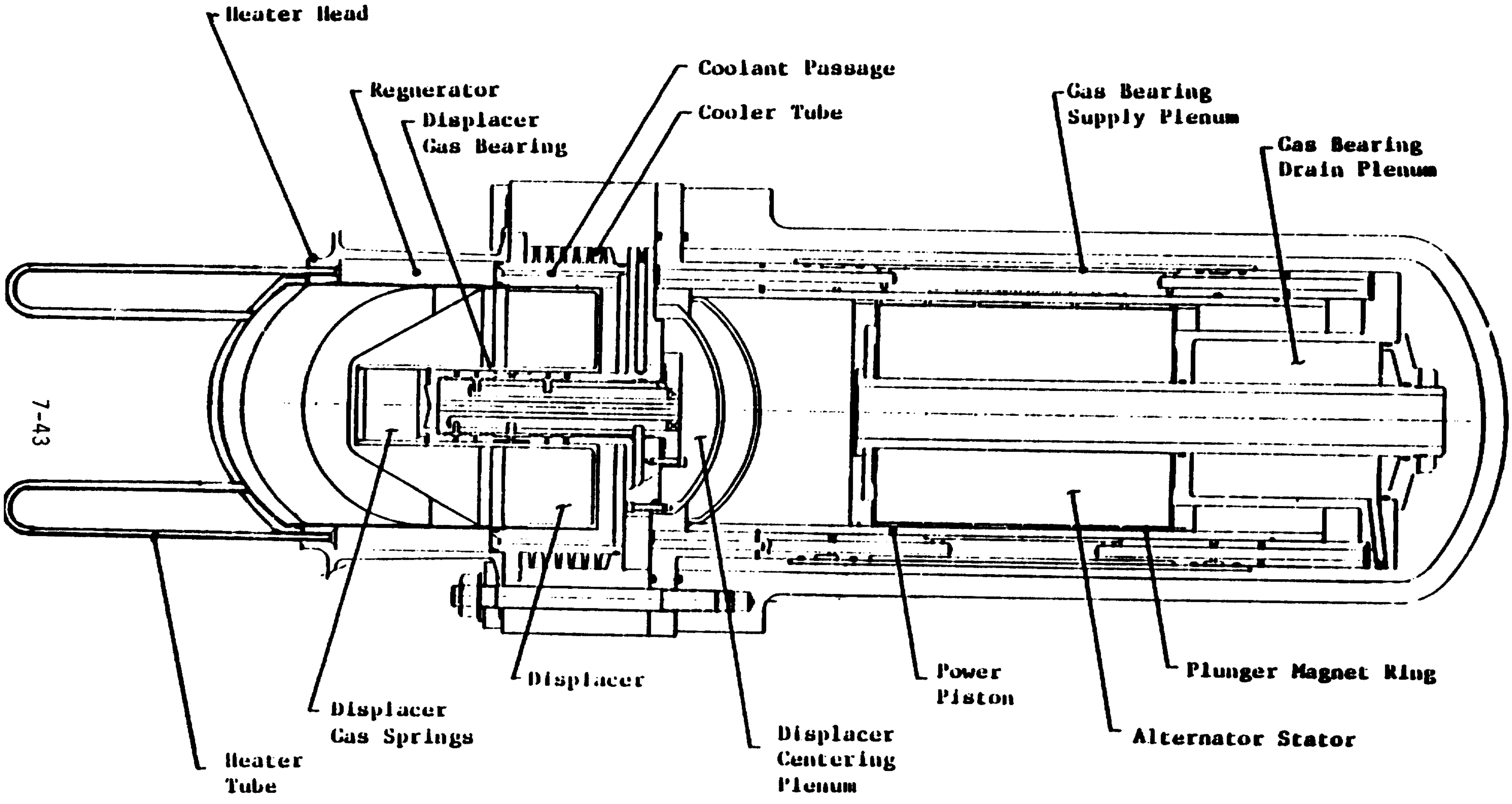

Figure 7.13 3 kW FREE PISTON ENGINE (MTI)

Table 7.6

PERFORMANCE PROJECTIONS FOR SILENT POWER GENERATOR SYSTEM*

Power Output	3 kW
Length Overall	75 cm
Heater Head Outside Diameter	25 cm
Piston Diameter	13 cm
Displacer Diameter	13 cm
Heater Tube Length	10 cm
Heater Tube Diameter	0.356 cm
Heat Input	9400 watts
Charge Pressure	34.2 Bar
Efficiency	.32
Operating Temperature	700°C
Life	30,000+ hours

* Based on MTI System Concepts and Layouts.

piston Stirling engine system with hydrogen working gas at 500 psi mean pressure. The permanent magnet alternator allows the unit to be hermetically sealed for long life. The output of the generator is 60 Hz, 240 volt ac, 1 Ø and is usable without further modification.

Table 7.7 compares the performance capabilities of free piston Stirling engines with the general needs of this application class and those of a representative I.C. engine. The I.C. engine is inappropriate for many applications of potential interest, such as the solar application of the conceptual design, where an external heat input is required. However, the life requirements of the Stirling engine in this application class still need to be demonstrated.

Automotive and Automotive Derived Power:

As indicated in previous sections, the mobile power class of applications also includes a number of potentially attractive stationary applications, such as commercial heat pump drives. As indicated in Table 7.3, the life requirements of automotive and many of the stationary applications differ significantly (3500 hours for automotive and 20,000+ hours for most stationary). Reference 18 indicates, however, that basic automotive Stirling configurations could be derated and/or modified to better meet the life and reliability requirements of non-automotive applications. These diverse applications could, therefore, be served by a small number of engine systems which can be adapted (derated, etc.) to meet different application needs.

For purposes of a conceptual design, an automotive engine was assumed to be derated and modified for use in a commercial size heat pump system. This application was selected since it might be an early application which could take direct advantage of automotive technology and, at the same time, result in engine experience which would accelerate their use in vehicular propulsion applications.

Figure 7.14 is a conceptual illustration of an automotive engine, derated and installed in a commercial size heat pump system. In this case the engine

Table 7.7

COMPARISON OF CONCEPTUAL DESIGN PARAMETERS WITH APPLICATION REQUIREMENTS – SILENT POWER SYSTEM

	Application Class Requirements	Representative[1] Engine Capability	Stirling Engine Capability[3]
Power Level	1-50 kW	35	1-50
Efficiency	25-35%	~ 30	25-35%
Emissions	Application Dependent	Questionable for many applications	Inherently low and within requirements
Noise Level	Low Noise Important (Less than 65-75 dBa @ 1 meter)		
Heat Recovery	Application Dependent	Note 2	Note 4
Maintenance Interval	1-2 times/yr (2,000-5,000 hours)	1,000 hours	TBD[5]
Life before Major Overhaul	7-15 yrs 15,000-25,000 hours	~ 30,000 hours	TBD[5]
Multi Fuel Capability	Important in solar and energy storage applications	Very limited	Excellent
Cost	\$250-\$500/kW	\$ ~ 240/kW	Higher end of cost range probably achievable
Weight	7-20	20 kg/kW	Within range
Size	0.03-0.08	0.03 M^3/kW	Within range

1. Assumed to be a Caterpillar 3304, derated to 35 kW.
2. From exhaust gases and cooling water.
3. Consistent with projections for conceptual design.
4. Readily available from coolant water with minimal additional cost.
5. Need to be demonstrated by future program initiatives.

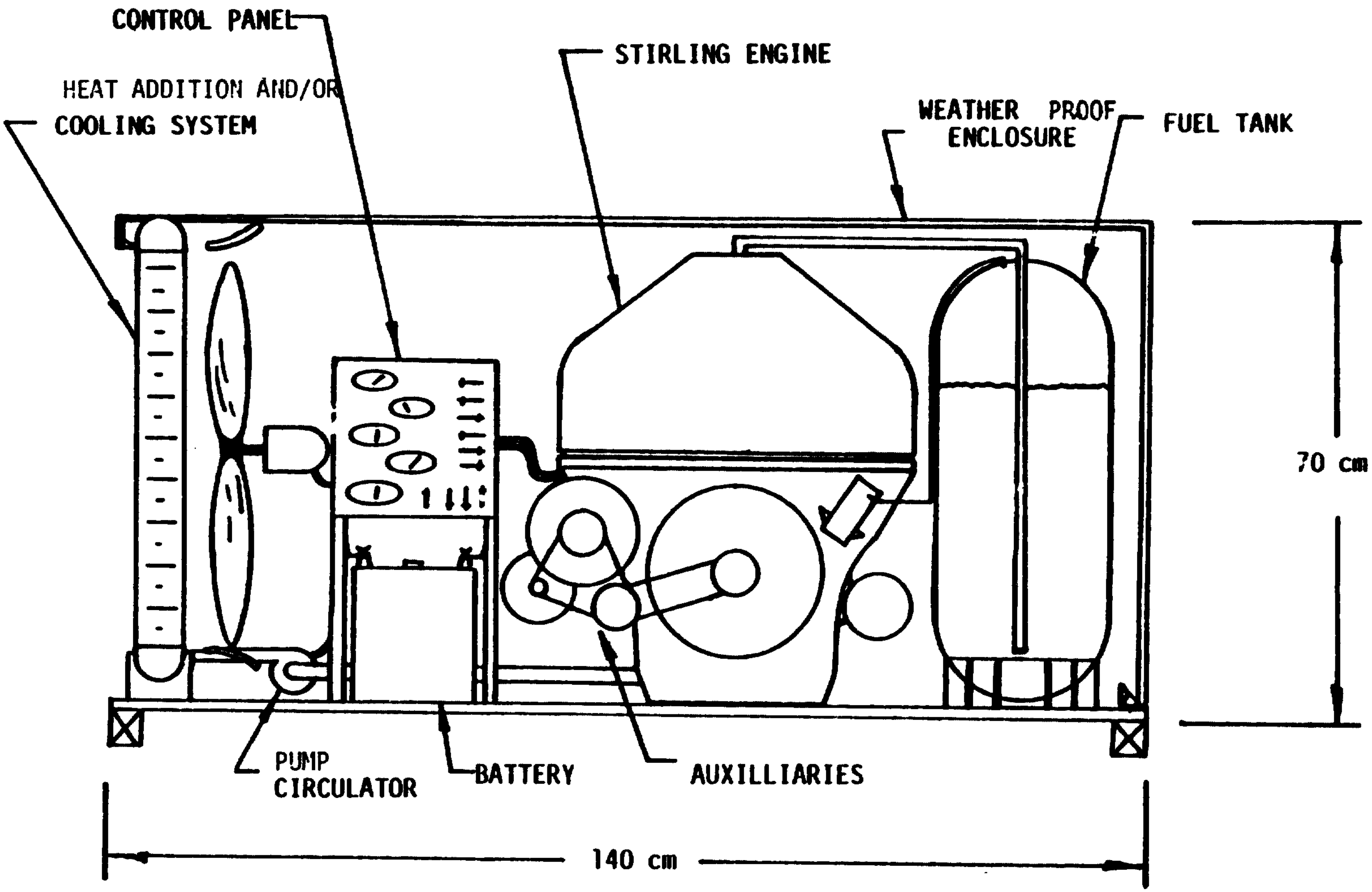

Figure 7.14 CONCEPTUAL DESIGN OF AN AUTOMOTIVE DERIVED ENGINE IN A COMMERCIAL HEAT PUMP APPLICATION

system is comprised of the prime mover and auxilliaries attached to the engine (such as blower, pump, starter, etc.) as well as the cooling system (radiator, fan, coolant pump used only in the air conditioning mode), battery, control system, fuel tank, weatherproof enclosure, mounting frame, etc. This is all in addition to the heat pump part of the system. The engine will be rated at 30 kW output and would provide approximately 30 tons of cooling or approximately 500,000 Btu of heat/hr in a heating mode, assuming a heat pump COP of 2.5 and a 35% efficient engine.

The engine package shown would meet the operational requirements of this application. Also, cost studies done in support of the automotive program indicate good promise in meeting the cost goals associated with the higher prices of stationary applications which such engines might serve. For example, the commercial heat pump engine could have costs in the $400/kW range as compared with light duty vehicular propulsion cost requirements of less than $20/kW.

Figure 7.15 is a schematic of the closest commercial practice to a mobile power engine system. This is the MOD 1 engine developed as part of the automotive Stirling engine program at NASA Lewis. Through operating variations and modified construction the engine could be designed for long life applications, taking advantage of past and ongoing programs to develop an efficient, quiet, multifuel engine. Table 7.8 summarizes the projected characteristics of this engine at the conclusion of the ASE program (R.E.S.D.). As indicated the engine, rated in its automotive application is designed for 60 kW peak output and operates with hydrogen working gas.

Table 7.9 compares the performance characteristics of an automotive derived Stirling engine to the requirements of this application class and to a representative I.C. engine. As indicated, the Stirling engine appears very favorable on most counts. The relatively high cost ($300+/kW) of derated I.C. engines suitable for these applications provides the Stirling engine with additional flexibiity in meeting cost goals.
The life requirements, however, are a major issue requiring resolution.

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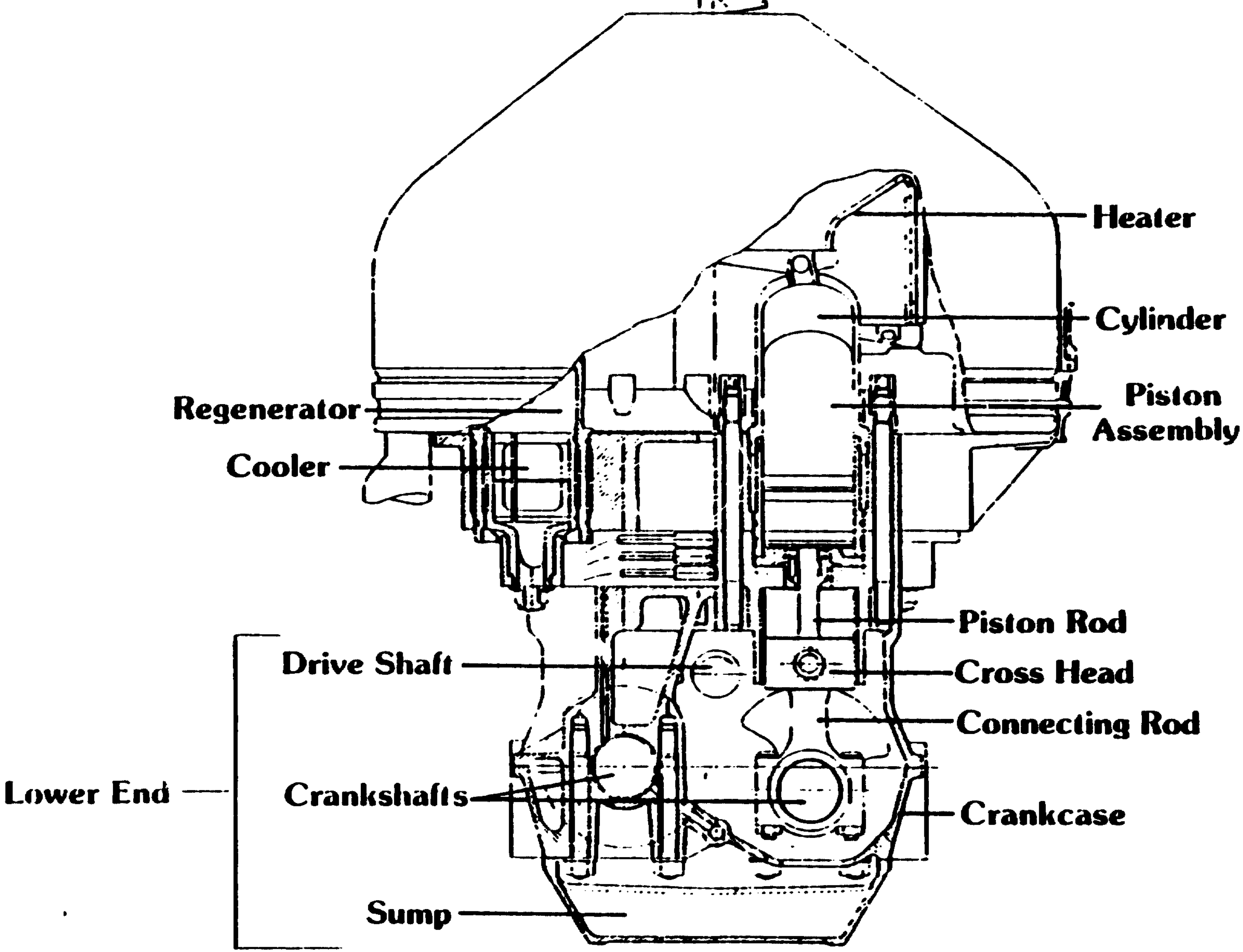

Figure 7.15 30 kW DERATED AUTOMOTIVE ENGINE (MOD-I) FOR COMMERCIAL HEAT PUMP APPLICATION

Table 7.8

PERFORMANCE PROJECTIONS FOR RESD AUTOMOTIVE STIRLING ENGINE

CHARACTERISTICS	FULL-LOAD POINT $\overline{P}$ = 15 MPa N = 4000 rpm	PART-LOAD POINT $\overline{P}$ = 5 MPa N = 2000 rpm	MAXIMUM EFFICIENCY POINT $\overline{P}$ = 15 MPa N = 1100 rpm
Indicated Power (kW)	73.3	15.0	24.8
Friction (kW)	9.6	2.0	2.2
Auxiliaries (kW)	3.6	0.8	0.5
Net Power (kW)	60.1	12.2	22.1
External Heating Efficiency (%)	90.5	91.7	92.4
Net Efficiency (%)	34.2	37.7	43.5

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Table 7.9

Comparison Of Conceptual Design Parameters With
Application Requirements --
Automotive Derived Total Energy/Heat Pump Drive

	Application Class Requirements	Representative[1] Engine Capability	Stirling Engine Capability
Power Level	30-100 kW	70 kW	Can Cover Range
Efficiency	30-40%	34%	35-40%
Emissions	Site Specific		
Noise Level	Site Specific (Only Local Regulation at Present)	Questionable for Many Applications	Inherently Low and Within Requirements
Heat Recovery	Primary Importance	From Exhaust Gases, Oil Sump and Coolant; at Some Additional Cost	From Coolant; Minimal Additional Cost
Maintenance Interval	1-2 Times/Yr (2,000-5,000 Hours)	1,000 Hours	TBD[2]
Life Before Major Overhaul	7-15 Yrs – 15,000-25,000 Hours	~30,000 Hours	TBD[2]
Multi Fuel Capability	Highly Desirable, but Not Critical	Very Limited	Excellent
Cost	\$200-\$500/kW	\$150-\$300/kW[3]	Higher End of Cost Range Probably Achievable
Weight	7-20 kg/kW	10 kg/kW	Within Range
Size	.005-.015 m^3/kW	0.015 m^3/kW	Within Range

1. Assumed to be a Caterpillar 3304.
2. Need "to be demonstrated" by future program initiatives.
3. Depending on System Configur...on.

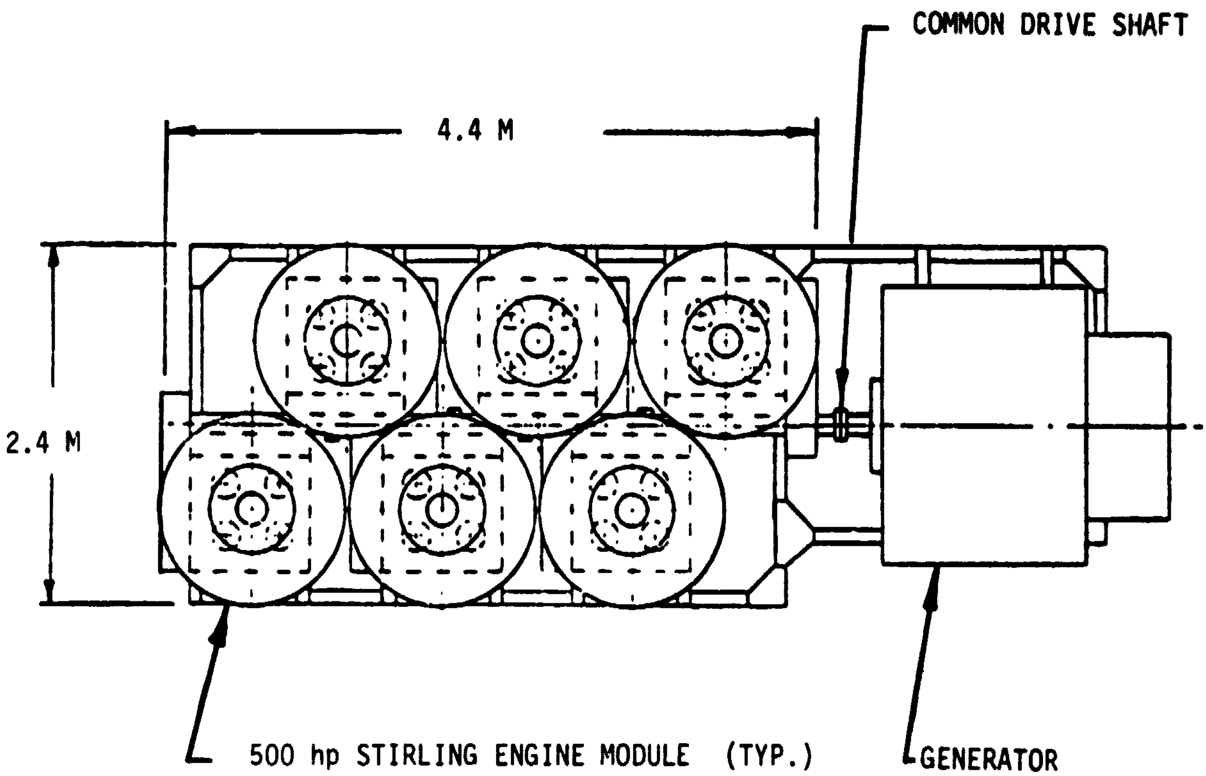
Large Stationary Power:

As indicated in Table 7.4 of the previous section, the performance requirements for a large stationary power system are quite severe for efficiency, life, maintenance, and emissions. On the other hand, the weight, size, cost, and noise requirements are not so severe.

The basic configuration selected for this application class is that of an upscaled automotive engine. It is unlikely that the relatively small market for this size engine would warrant a specially designed engine. Through derating and modified design (upsizing, more robust construction, heavier materials, etc.) the engine would be designed for high efficiency, long life, and low maintenance. Several characteristics of the Stirling engine on this application are:

- o Relative ease of switching to a variety of fuels, particularly liquid and gaseous fuels (such as heavy fuel oils, light distillates, gasoline, alcohol, methane, propane, sewer gas, etc.) as well as the potential to use solid fuels.
- o The high efficiency attainable with the Stirling engine is of critical importance in this application.
- o In these applications, the additional size and weight of an engine designed for long life are not of great significance.
- o The low emission characteristics of the Stirling engine could be very important in some applications: the output and cost constraints of the engine could warrant sophisticated combustion systems to mimninize the emissions.

There is relatively little work currently underway to develop large stationary power Stirling engines. Figure 7.16 is a schematic of one of the few large Stirling engines studied, resulting from an Argonne Study by Amtech. This design happens to be based on coal combustion but would more likely be operated on fuels such as oil or gas in the near-term. Table 7.10 compares projected design attributes of the large stationary Stirling power units with application class requirements and the performance capabilities of a medium speed Diesel



— 6 MODULES FOR 3000 hp TOTAL POWER

Figure 7.16 CONCEPTUAL DESIGN OF A LARGE STATIONARY POWER SYSTEM

Table 7.10

COMPARISON OF CONCEPTUAL DESIGN PARAMETERS WITH APPLICATION REQUIREMENTS - STATIONARY POWER

	APPLICATION CLASS REQUIREMENTS	REPRESENTATIVE[1] ENGINE CAPABILITY	STIRLING ENGINE CAPABILITY[3]
POWER RANGE	500-5000 kW	1500-3000 kW	Can Cover Range
EFFICIENCY	30-40%	34%	30-40
EMISSIONS	To Meet Local Standards	Questionable for some applications	Can probably meet all requirements
NOISE LEVEL	Application Dependent (No Federal Regulation at Present)		
HEAT RECOVERY	Application Dependent	Note 2	Note 4 TBD[5]
MAINTENANCE INTERVAL	4,000-8,000 hours		TBD[5]
LIFE BEFORE MAJOR OVERHAUL	30,000$^+$ hours	Limited fuel flexibility	
FUEL FLEXIBILITY	Range of heavy and light liquid fuels desireable Ability to burn coal could become advantage		Good flexibility with all liquid and gaseous fuels Potential to burn coal in advanced systems
COST	\$250-450/kW	\$250$^+$/kW	
WEIGHT	Not Critical (20-50 kg/kW)	10.6	
SIZE	Not Critical (.030-.100 M^3/kW)	0.015	

1. Assumed to be Fairbank Morse Model 38TD with characteristics from Table 5.3.
2. From exhaust gases and cooling water.
3. Consistent with projections for conceptual design.
4. Readily available from cooling water with minimal additional cost.
5. Long life and high reliability requirements are "to be demonstrated".

engine. Heavy duty internal combustion engines are seen to have very competitive performance characteristics (high efficiency, long life, etc.) in this application area. However, the Stirling engine has a wider fuel flexibility and fewer emission problems which might make their use attractive in the future.

8.0 POSSIBLE EFFECTS OF TECHNOLOGY, ECONOMIC CONDITIONS, AND REGULATORY CHANGES

The general environment in which the Stirling engine must compete is changing, as a result of regulatory trends, escalating energy costs, and improvements in competitive power system technologies. These trends could be critical in determining the competitive position of Stirling engines in many of the applications of primary interest. For discussion purposes these issues are divided as follows:

- o Improvements in power system technologies which could impact on the competitive position of Stirling engines.
- o Trends in noise standards which could favor Stirling engine use in such applications as heat pumps.
- o Fuel and electricity cost trends.

The above issues are discussed briefly below.

8.1 Effects of Advances in Technology

There are a number of power system options which are already in use or could be considered for all the potential Stirling engine applications. In many cases the technical performance of these alternatives are improving as a result of extensive development efforts by government and private sector organizations; i.e., the competition for Stirling engine systems represents a "moving target". It is important to be aware of major trends with competitive systems in order to realistically assess the potential for Stirling engines. Alternative power systems which are being improved include:

- o High efficiency, multifuel, internal combustion engines,
- o Fuel cells,
- o Thermoelectrics,
- o Thermionics,
- o Photovoltaics,
- o "Packaged" Rankine cycle engines,
- o MHD, and
- o Brayton cycle engines.

Not all these developments directly impact on Stirling engine prospects. For example, MHD is a long term development and one which is applicable only to large scale (100 MW+) power generation - well above that considered in this study.

Other developments could, however, significantly impact Stirling engine prospects. Several of these developments and their potential impacts in specific application areas are reviewed below.

o I.C. Engines

A number of recent concepts either currently used or under development are aimed at making the conventional I.C. engine more fuel efficient and/or lower in exhaust gas emissions. A brief description of some examples follows.

o Electronic Ignition

For several years specialty engines have used solid state ignition systems to accurately control the timing and duration of the spark used to ignite the air/fuel mixture in the engine. These have come into much more widespread use particularly in automotive applications, to more accurately control the combustion process and thereby increase engine efficiency and reduce emissions. They have the added benefits of increasing spark plug life and decreasing routine engine maintenance.

o Turbo Charging

Turbo charging has been in use for several years in specialized applications where high power density is desirable (such as in aircraft or race car engines). It consists of the extraction of waste energy in the exhaust gas stream and using that energy to increase the air/fuel mixture flow rate into the engine on the intake side. The mechanical arrangement is generally two turbine wheels (an expander and a compressor) mounted on the same shaft, expanding the exhaust gases to ambient pressure, while compressing the intake air/fuel mixture. This has the advantage of increasing the efficiency and power output of a given engine displacement, without significantly affecting emission characteristics, at times when the engine is not fully utilizing the turbo charger.

o Turbo Compounding

This technique is similar to turbo charging, except that part of the mechanical energy extracted from the exhaust stream is used directly to augment the shaft output of the engine, and not only to compress the intake fuel/air mixture. This technique is being investigated to increase engine efficiency and power output over an engine configuration without turbo compounding.

o Fuel Injection

Although required on Diesel engines, fuel injection for gasoline powered passenger car engines is a relatively recent development. The precision with which the fuel can be metered into the engine has an important beneficial effect on exhaust emissions while at the same time improving engine performance. In this direction, General Motors has recently introduced a system called "throttle body injection", that is intended to achieve fuel control similar to that of fuel injection, without the complexities normally associated with conventional systems.

o Adiabatic Diesel Engine Operation

The operation of Diesel engines without a cooling system, in a high temperature mode, is referred to as the Adiabatic Diesel Cycle and is under investigation as a technique for achieving very efficient Diesel engine operation. Other advantages are a lighter weight engine, elimination of the cooling system and its associated equipment and parasitic power drains, as well as smaller size. These engines are in fact being considered as power plants for future propeller driven aircraft.

o Bottoming Cycles for Stationary Engines

The high temperature exhaust stream from an engine can often be used to operate a Rankine cycle engine, to produce additional shaft power for the same fuel input (or conversely the same output for less fuel input). This concept is often considered for use with large stationary engines such as gas turbines or Diesel engines for utility power generation, with relatively high duty cycles. However, there is a significant effort to develop bottoming cycle engines for use with the exhaust gases of Diesel engines in heavy duty trucks. These systems have already demonstrated their ability to decrease fuel consumption in trucks by over 15%.

o Photovoltaics

One of the potentially promising applications for Stirling engines is as a very high efficiency power converter within a solar thermal power system. If successful, this application shows potential for large markets on a worldwide basis. However, one issue facing all solar thermal power developments is the competition from photovoltaics. The present cost of photovoltaic panels is about $10,000/kW. However, this cost is projected by both DOE and industrial sources to drop by close to an order of magnitude over the next 5-10 years. Cost reductions of this magnitude in photovoltaics would increase the uncertainty associated with all solar thermal power developments - including those using Stirling engines as the power system.

o Fuel Cells

Fuel cells have many of the same advantages as do Stirling engines, such as low noise and vibration, high efficiency, and low exhaust emissions. They do not, however, have the fuel flexibility and the ability to produce mechanical power as Stirling engines. Nevertheless, where clean fuels are available (including natural gas) they would be directly competitive with Stirling engines in stationary applications. For example, fuel cells are under active development by the gas industry for use in residential and commercial total energy systems and as silent generators for use by the military.

The successful commercialization of fuel cell systems could therefore significantly impact on Stirling engine prospects in several of the potentially favorable market areas.

- **Prepackaged Rankine Cycle Power Systems**

Primarily as a result of heat recovery and solar energy programs, several firms in the U.S., Europe, and Japan have developed packaged Rankine cycle power systems with capacities in the 10-200 kW power range. These systems share the advantage of Stirling engines of having a multifuel capability allowing them to be operated with solar energy, isotopes, thermal storage, and "dirty" fossil fuels (biomass, synthetics, etc.). Particularly in larger capacities (100 kW), such systems provide a formidable alternative to Stirling engines. The performance of such systems is likely to improve if their use in heat recovery, co-generation, and solar power increases as projected.

8.2 Effects of Emission and Noise Standards

One of the primary incentives behind Stirling engine developments has been to develop a high efficiency engine with low exhaust emissions. This issue is particularly important in automotive, heat pump, mining, and other applications. Trends in emission standards which could effect the potential for Stirling engines include:

- Automotive standards.
- PSD (Prevention of Significant Deterioration), which has site-specific implications.
- Standards based on current local air quality rather than individual engine emissions.
- Trend toward relaxing standards for alternative and coal-derived fuels.
- Indoor air quality standards.
- Mine standards.

Many of the environmental regulations are directed at large utility or industrial facilities which are not germaine to the scope of this program. Emission standards which are most likely to affect the potential for specific Stirling engine applications are discussed briefly below.

Automotive Emission Standards

The automotive application area is one where low emissions are an important requirement for any engine. The emission standards which currently apply for model years through 1982 are listed in Tables 8.1 and 8.2. The Environmental Protection Agency is not planning to change these standards until at least 1983. However, there is still serious concern on whether existing standards are sufficiently stringent to protect the environment over the longer term. This concern is particulary strong in relationship to potential carcinogenic particulates from Diesel engines which are a major competitive system for lower fuel consumption automotive engines. The Stirling engine has demonstrated its potential for significantly reducing emissions as compared to present standards and for eliminating the particulate problems associated with Diesel engines. A successful automotive Stirling engine development would, therefore, provide the country with additional flexibility in setting emission standards should new data indicate that more stringent standards are necessary to protect the public welfare.

Existing vehicular engines are capable of meeting current emission standards, albeit with some difficulty. In the case of spark-ignition engines, this is achieved predominantly through the use of three-way catalysts in the exhaust line which provide simultaneous reduction of HC, CO, and NO_x emissions. The principal disadvantage of this approach is that the operating window is very narrow requiring the engine to run at air/fuel ratios near stoichiometric. This presents problems in terms of fuel control complexity and optimizing vehicle fuel economy. In the case of Diesel engines, the uses of a catalyst is greatly complicated by the potential for plugging by particulates. Emission reduction is instead attained through combustion modifications involving close control of parameters such as engine timing, injector design, and spray pattern. These approaches suffer the same disadvantages in terms of complexity and fuel economy as the catalytic approach for spark-ignition engines. The low-emission characteristics inherent in the Stirling engine represent a potentially significant competitive edge over alternative vehicular power plants.

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TABLE 8.1

PRESENT AND FUTURE FEDERAL
PASSENGER AUTOMOBILE EMISSION STANDARDS

in gm/mile

Model Year	HC	CO	NO_x	Particulates
		Actual		
Precontrol	8.8	87.0	3.6	-
		Mandated		
1975	1.5	15.0	3.1	-
1976	1.5	15.0	3.1	-
1977	1.5	15.0	2.0	-
1978	1.5	15.0	2.0	-
1979	1.5	15.0	2.0	-
1980	0.41	7.0	2.0	-
1981	0.41	3.4	1.0	-
1982	0.41	3.4	1.0	0.6
		Possible		
1983	0.41	3.4	1.0	0.6
1985	0.41	3.4	1.0	0.2
1990	0.41	3.4	0.4	0.2

Sources: Environmental Protection Agency and
Arthur D. Little estimates

TABLE 8.2 **EMISSION STANDARDS FOR CONTROL OF AIR POLLUTION FROM MOBILE SOURCES**

Mobile Sources	Hydrocarbons 1978	Hydrocarbons 1979	Hydrocarbons 1980	Hydrocarbons 1981,	Carbon Monoxide 1978	Carbon Monoxide 1979	Carbon Monoxide 1980	Carbon Monoxide 1981,	Nitrogen Oxides 1978	Nitrogen Oxides 1979	Nitrogen Oxides 1980	Nitrogen Oxides 1981,
Light duty vehicles[a]	1.5	1.5	0.41	0.41	15	15	7.0	3.4	2.0	2.0	2.0	1.0
Light duty truck[a]	2.0	1.7	1.7	1.7	20	18	18	18	3.1	2.3	2.3	2.3
Low emission vehicles[a]	0.08	--	--	--	0.7	--	--	--	0.4	--	--	--
Motorcycles[d]	5-14[e]	5-14[e]	5	5	--	17	12	12	--	--	--	--
Gasoline-fueled heavy duty[b,c] engine	--	1.5	1.5	1.5	40	25	25	25	16[f] --	10[f] or 9.5	10[f]	10[f]
Diesel-fueled heavy duty[b,c] engine	--	--	1.5	1.5	40	--	25	25	16	10[f] or 9.5	10[f] or 9.5	--

[a]Values for standards reported in grams per vehicle mile.

[b]Values for standards reported in grams per brake horsepower.

[c]Opacity limitation-20% during acceleration mode; 15% during lugging mode; 50% maximum during either mode.

[d]Values for standards reported in gm/km.

[e]Dependent on displacement from 170-720 cc.

[f]Nitrogen oxide and hydrocarbons.

Source: 40 CFR (Code of Federal Regulations), Part 86

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Prevention of Significant Deterioration (PSD)

The PSD regulations (40 Code of Federal Regulations, part 50, Clean Air Act Amendment of 1977) are highly judgemental in nature and state that should a system or project result in a significant deterioration of the air quality from that existing prior to the project, it may be stopped. This regulation is intended primarily to apply to large (industrial or utility) projects but could, in principle, be applied to smaller commercial or even a multiplicity of residential projects. For example, it was recently used to delay for 3 years the implementation of a Diesel engine driven total energy plant in Boston, MA.

This law could be used to discourage the use of engine driven heat pumps or total energy systems of all sizes if the engines resulted in significantly higher emission levels than those from gas or oil furnaces now commonly used. As a result, Stirling engines would have a significant advantage over I.C. engine driven systems in such applications and, in fact, Diesel engines may be found to be unacceptable in many locations given their present emission characteristics.

Indoor Air Quality Regulations

In 1974, OSHA promulgated regulations establishing levels of pollutants that would be acceptable in the workplace atmosphere. These levels are time-weighted averages based on 8 hours per day or 40 hours per week exposure. For combustion pollutants the limits are as follows:

	PPM at 25°C and 1 atm
CO_2	5000
CO	50
NO_2	5

Source: 24 CFR (Code of Federal Regulations), Part 1910, Subpart Z, entitled, "Toxic and Hazardous Substances."

These regulations are often met in practice by using large amounts of ventilation air which increases blower power and heating costs.

These regulations would favor the use of low emission Stirling engines to power indoor vehicles such as fork lift trucks, floor sweepers, and people movers. However, in part, to respond to these regulations there has been a trend toward electric drives for such vehicles (replacing small I.C. engines often using bottled gas as a fuel). At present there are no equivalent standards for residential air quality.

Regulations in Mines

There are a number of Government regulations for vehicles used in underground mines, relating to ventilation requirements, noise, etc. as they affect health and safety of mine workers. For example, a current noise level limit of 90 db may be lowered to 85 or even 80 db in the near future. Exhaust emissions 10 ft away from the vehicle must be less than the following:

CO_2	0.5%
CO	100 ppm
NO_x	25 ppm
Aldehydes	10 ppm

These regulations tend to favor the development of the Stirling engine, with its low emissions and noise characteristics, as compared to the Diesel engine which is currently in use, where it is appropriate.

Noise Control Act

In 1972, EPA standards on noise were promulgated for railroad, highway, off-road vehicles, portable compressors, etc., which are shown in Table 8.3. The limits vary from 70 dB (off-road moped-type, below 170CC) to 90 dB (moving locomotives). With the help of silencer design, and design of effective sound barriers, present engines tend to meet most of the noise standards. Stirling engines would make it much easier to meet these standards without elaborate design of noise barriers. As far as residential equipment is concerned there are no equivalent national or statewide standards. There may, however, be relevant local codes which limit noise levels in residential areas.

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TABLE 8.3 NOISE REGULATIONS PROMULGATED OR PROPOSED

Noise Source		Noise Level in dBA	Date Effective
Locomotive--Stationary			
In gear		87	December 31, 1976
Idle		70	
Moving		90	
Railroad car--Under 72 km/hr		88	December 31, 1976
Over 72 km/hr		92	December 31, 1976
Motor carriers in interstate commerce--Under		86	October 15, 1975
--Over		90	
-- Full throttle stationary		88	
Medium and heavy trucks		83	January 1, 1978
		80	January 1, 1982
Exemptions for fire trucks and mobile homes			
Portable air compressors--<250 ft^3/min		76	January 1, 1978
-->250 ft^3/min		76	July 1, 1978
[a]Crawler tractors	20-199 HP	77	March 1, 1981
		74	1984
	20-450 HP	83	1981
		80	1984
[a]Wheel loaders	20-249 HP	79	1981
		76	1984
	250-500 HP	84	1981
		80	1984
[a]Wheel tractors	20+ HP	74	March 1, 1981
[a]New truck-mounted solid waste compactors		78	January 1, 1979
		75	1982
[a]Exterior bus noise		83	January 1, 1979
		80	1983
		77	1985
[a]Interior bus noise		86	1979
		83	1983
		80	1985
[a]Street motorcycles		83	January 1, 1980
		80	1982
		78	1985
[a]Moped-type		70	1980
Offroad below 170 cc		83	1980
		80	1982
		78	1985
[a]Offroad above 170 cc		86	1980
		82	1983

[a]Proposed as of August 1979

Source: 40 Code of Federal Regulations Parts 203 and 204

8.3 Effect of Fuel Availabili ; and Cost

Fuel availability and the cost of conventional fuel have major impacts on applications and use of engine types. Since Stirling engines have multifuel capability, fuel switching is possible, and therefore, may offer advantages over gasoline, Diesel, or gas turbines, which are specifically designed for a particular fuel. The availability and cost of a particular fuel is pivotal to the use of most conventional engines. Trends which are likely to be factors in influencing the commercialization of Stirling engines could include:

- o Conventional fuels are expected to have fairly constant supplies for the next two decades.
- o Prices for conventional fuels (in real dollars) will approximately double by the year 2000.
- o The cost of electricity is likely to increase at a lower rate than natural gas or oil.
- o Price difference between distillate and residual oil is expected to remain constant.
- o Liquid fuels from coal and shale oil are less likely to be produced in signficant quantities by the year 2000.

Assessing the full range of effects of the above observations on the potential for various power system options is a very complex undertaking. However, some important observations can be made relative to their impacts on several of the Stirling engine applications of interest. Several such observations are discussed below.

Multifuel Capability

One incentive behind recent programs in large stationary Stirling engines was their capability to utilize coal and other "dirty" fuels such as heavy synthetic oil. This incentive, in turn, resulted from a perception that natural gas and liquid fuels would be in short supply for industrial applications. This scenario does not appear at this time to be generally valid, i.e., over the next two decades gaseous and liquid fuels will probably be generally available which will allow for operating conventional power options. There appears, therefore, to be only limited incentives at this time to develop (5,000 kW) coal fired power systems - particularly in the relatively low power range (5,000 kW) considered in this study.

Heat Pump/Total Energy Applications

Heretofore the incentive to develop engine driven heat pumps or total energy systems has been the availability of low cost natural gas. Many observers project, however, that the price differential between natural gas and electricity will be decreasing in the 1980s. For example, some projections indicate that electricity cost should increase at a rate of 0-2% over the next decade in real dollars while that of natural gas will increase at 3-6% in real terms over the same period of time due, in part, to natural gas deregulation. The present spread between gas and electricity prices based on thermal value is approximately 3 to 1 (based on 5¢/kWh power and $5 per 1000 CF for gas).

A decrease in this spread would place more stringent initial cost and performance requirements on gas driven heat pumps to result in a large commercial market. Recent history suggests, however, that predictions of energy costs are still highly uncertain and many factors could significantly modify the energy cost scenarios referred to above. For example, a signficant increase in the demand for electricity over that assumed might result in escalating its cost if this requires adding costly new capacity.

Increasing Fuel Costs

The increasing costs of all fuel forms projected over the next decade provides an incentive to utilize highly efficient engines in all applications. Therefore, both the demonstrated efficiency (35%) and the projected efficiency potential (40%) of Stirling engines will become increasingly important in the future as energy costs increase.

It should be noted, however, that several competitive power systems (Diesel engines, fuel cells, internal combustion engine/bottoming cycle engine combinations) have efficiency levels comparable to those demonstrated in Stirling engines and that the efficiency characteristics of these alternatives may improve in order to meet consumer needs. The Stirling engine may be unique, however, in combining a very high efficiency potential with other important attributes such as fuel flexibility and low noise.

9.0 DISCUSSION OF RESULTS

Domestic Stirling Engine Applications:

The ranking charts of Section 7.1 indicated that Stirling engines could have significant advantages over conventional engines in a wide range of applications. A more quantitative comparison of application needs and Stirling engine configurations was provided as part of the conceptual designs of Section 7.3. In this section it was again shown that Stirling engines have already demonstrated many of the requirements needed to be attractive for use in application classes of potential interest. In particular, high efficiency, multi fuel capabilities, low noise and vibration, as well as low emission levels, are characteristics which have been demonstrated on test systems and there is no reason to believe that they cannot be achieved with a high degree of reliability on well engineered systems for all application classes considered. Even those characteristics which put Stirling engines at a disadvantage relative to more conventional options, such as size, weight, and cost may not be serious drawbacks in most of the applications of primary interests. The previous sections also indicated that many applications are now served or could be served by relatively high cost ($100+ per kW) heavy duty engines which provides additional flexibility in the design of suitable Stirling engine systems.

The application requirements of Section 7.0 are estimates for the minimum conditions which must be satisfied if a new engine is to show promise for making a meaningful market penetration and evolve over time into a significant commercial product. Clearly, exceeding these operational goals would further accelerate the introduction of a new engine. On the other hand, specialized applications might be satisfied even if all the design goals set forth were not achieved simultaneously.

Table 9.1 qualitatively summarizes the overall results of the previous sections and identifies those critical improvements in performance which Stirling engine systems must achieve to be consistent with the broad requirements in each application class. The identification of key development issues assumes that

Table 9.1

SUMMARY - STIRLING ENGINE STATUS AND DEVELOPMENT NEEDS

APPLICATION CLASS	TECHNOLOGY STATUS	IMPORTANT DEVELOPMENT NEEDS
Simple Rural Power	Recent testing indicates good promise for simple fired hot air engine	- Demonstrate life in excess of 10,000 hours with low maintenance requirements - Improve efficiency to 15-25% range
Silent Power	Testing of both free piston and kinematic engines have demonstrated most of technical requirements	- Demonstrate life in excess of 20,000 hours - Demonstrate capability of 2,000 hours operation without maintenance - Consistently achieve efficiencies in excess of [illegible]0%
Automotive and Automotive Derived Engines		
(a) Automotive	Testing has demonstrated most important operating requirements and projections indicate further improvements in efficiency	- Demonstrate life of 3,500 hours with low maintenance requirements - Demonstrate that efficiency projections can be achieved
(b) Automotive Derived	Same as automotive	- Demonstrate life in excess of 20,000 hours with low maintenance requirements
(c) Large Stationary Power	Design studies and automotive testing both show promise of achieving most of required operational characteristics	- Demonstrate life in excess of 50,000 hours - Demonstrate overhaul intervals in excess of 5,000 hours. - Demonstrate capability of 40% efficiency on range of liquid and gaseous fuels

ongoing activities are reasonably successful in achieving programatic objectives. For example, it was assumed that the off-design performance goals (off-design performance of free piston heat pumps is important, since the loads on the system vary with ambient air conditions) of the free piston heat pump programs can, in fact, be demonstrated, that efficiency projections for automotive systems will be achieved, and that automotive technology could be scaled-up to result in large stationary power units. With these assumptions, it is seen in Table 9.1 that there remains several critical development needs which are not adequately addressed by ongoing programs. A common theme for all application classes is the need to emphasize designs which are consistent with long life, low maintenance operation. The quantitative disparity between the life requirements of almost all applications of interest and the engine durability demonstrated to date is very large. All applications, except automotive and other light duty vehicular, require engine lifes (time between overhauls) in excess of 20,000 hours. On this important issue, the requirements of the automotive application are relatively modest, being only about 3500 hours.

If these life and reliability goals can be demonstrated without large compromise in other required features (high efficiency) or large increases in cost, the Stirling engine would be a highly competitive option in all but very light duty applications. On the other hand, without achieving (or at least approaching) the life and reliability objectives summarized in Table 9.1 the other desirable attributes of the Stirling engine will not be sufficient to result in commercially viable systems.

Also indicated in Table 9.1 is the need to consistently demonstrate high efficiency levels in order to satisfy application class requirements. This is due to the fact that Stirling engines must often compete with I.C. engines which can have efficiencies ranging from 25% for smaller gasoline engines to 40% for larger, low speed, Diesel engines. It will be important for Stirling engines to show a distinct efficiency advantage to provide an incentive to pursue their development. This is especially true for automotive applications where lower fuel consumption would be a major incentive to off-set higher first costs (by as much as 50%), and larger size and weight. These high efficiency goals are, in fact, stated goals of ongoing programs. The need to actually demonstrate a consistent capability to meet these goals is shown in Table 9.1 to emphasize their importance.

The important development needs for Stirling engines, i.e., most critically to demonstrate longer life and higher reliability, are common to all the application classes. The overwhelming need in this area should strongly guide future program initiatives so that resources can be focussed on addressing this critical issue. As stated previously in this report, present programs have successfully emphasized achieving other important operational goals (low emissions, lower cost, etc.) and system issues with relatively modest resources directed toward technology developments to specifically address life and reliability questions.

All the application classes share some common technical issues impacting on life and reliability: namely piston seals, shaft seals, and high temperature combustor/heater head subsystems. As indicated in Section 6.0, the details of the technical requirements for those subsystems can differ significantly between applications and system configurations. For example, non-contacting gas bearings in free piston engines offer the potential of very long engine life, whereas automotive kinematic engines require sliding seals which have a shorter, defined life based on wear. Despite these differences, it appears that there is a high degree of commonality between the essential issues of life and reliability which face each different Stirling engine application class. As a result, Stirling engine development programs for obstensibly different applications might have a high degree of overlap in their development needs if they address the most critical issues. This could provide additional opportunities to more effectively use limited resources to address basic technical issues common to a range of Stirling engine systems.

There are a number of programs underway to develop advanced Stirling engine components and system concepts. These include hydraulic methods of extracting power from free piston engines, swashplate drive mechanisms to allow for variable power operation at constant working gas pressure levels, and heat pipe integrated heater heads to allow more flexibility in interfacing heat sources with the high heat flux needs of the Stirling engine heater heads. These and other advanced technology development programs could eventually improve the cost/performance characteristics of Stirling engine systems. However, given the rather embryonic stage of most of these advanced developments, their potential impact would probably not be demonstrated for at least 3-5 years (even assuming consistent funding). Also, each of these advanced developments introduces a new set of potential technical problems. As a practical matter, therefore, the present Stirling engine technological base will in large part have to be utilized to demonstrate that Stirling engines can achieve the operational characteristics set forth above, if this is to be done over the next few years.

Foreign Stirling Engine Applications

The study summarized in this report has emphasized domestic applications of Stirling engine systems. However, if Stirling engines are successfully developed, they would have worldwide applicability. Examples that illustrate the growing potential for Stirling engines in two foreign market areas are illustrated in Appendix E. In Japan, for example, a strong incentive to accelerate the use of gas fired heat pumps and total energy systems has been prompted by government policies to even out large seasonal variations in electricity and gas. Emphasis is being given to using Stirling engine drives in the residential and light commercial capacity ranges. The other example cited is the large potential in developing countries for small biomass fired Stirling engines to satisfy critical needs for irrigation, refrigeration, and village lighting, as an alternative to high operating cost Diesel generators or grid extensions. In both examples, it is quite likely that foreign manufacturers will rely heavily on the large U.S. based R&D programs in developing their systems. It is, therefore, important that both government and corporate programs consider this export potential as well as the domestic markets.

Summary Statement

The overall objectives of this study were to assess the potential for Stirling engine applications in the .5-5000 hp range, and to define the technical needs for Stirling to be successful in these applications. Over one hundred engine applications were identified and grouped into the following ten application classes. The applications in each class have a high degree of commonality in technical performance and cost requirements.

- o Heat Pump/Total Energy
- o Industrial Equipment
- o Space Power
- o Remote/Multifuel
- o Low Usage Equipment
- o Military Quiet Power
- o Mobile Power (Light)
- o Mobile Power (Medium)
- o Solar Thermal
- o Large Stationary

For each of the application classes, the Stirling engine was compared to conventional engines under the assumption that objectives of ongoing Stirling engine development programs could be met. The engines were compared on the basis of twelve characteristics (fuel flexibility, low emissions, high efficiency, etc.) that are important to a large number of applications. A numerical method, guided by judgmental factors, was used to assess the relative ranking of Stirling and conventional engines.

United States Market

The results of the assessment of potential Stirling engine applications in the United States indicated the following.

- o Stirling engines showed favorable potential for all applications except the Low Usage Equipment Class (lawn mowers, etc.).
- o Favorable Stirling engine application classes, which are currently served by conventional engines, represent a potential market of about 13 million engines per year.

- o Stirling engines ranked very high relative to conventional engines in the following four application classes that are not now served by conventional engines.
  - Heat Pump/Total Energy
  - Space Power
  - Remote/Multifuel
  - Solar Thermal

There is, however, no present commercial practice on which to base market projections.

Four Stirling engine conceptual designs were defined that could address all of the nine favorable applications. These are briefly described as follows:

- o Rural Power System - A low power (1-20 kW) hot air, kinematic engine of very simple, rugged construction.

- o Silent Power System - A low to medium power (3-30 kW) kinematic or free piston engine for silent power generation.

- o Automotive and Automotive Derived Power System - A medium power (3-100 kW) compact automotive derived power system for vehicle propulsion and stationary application.

- o Stationary Power - A high power (500-5000 kW) prime mover for large scale power generation.

Technology Needs

There remain some development needs which have not been adequately addressed by ongoing development programs. Achievement of the following needs would help to speed up the acceptance of the Stirling engine in the favorable applications.

- Demonstrate Stirling engine life consistent with the needs of each favorable application class, and show that the engine can meet the maintenance requirements.
- Consistently achieve a distinct efficiency advantage over the I.C. engine competitor in order to provide an incentive for Stirling engine acceptance.
- Emphasize Stirling engine designs - a modification of engines of present development programs - which are consistent with long life, low maintenance operation. (Example: Stationary engine derived from automotive engine.)

If life and reliability goals can be demonstrated without large compromises in efficiency, or increase in cost, the Stirling engine can be a highly competitive option for use in all nine application classes.

Foreign Markets

Developing Countries

A biomass fired Stirling engine (Remote/Multifuel application class), using indigenous fuels, is an attractive power source alternative to Diesels and photovoltaic systems in developing countries. The value of this potential foreign Stirling engine market may total nearly 200 million dollars by 1990. This value corresponds to a power generating capability of 200 MW, or 40,000 5 kW engines.

Japan

Government policies call for gas fired systems to displace 30% of the electricity now used in air conditioning functions in Japan by 1990. Additional actions relative to R&D funding, gas pricing, and tax incentives have been taken by the government to accelerate the introduction of gas fired systems - Stirling powered, and others. For this purpose, the government has initiated a 6 year, 40 million dollar program, in cooperation with industry and universities, to develop 3 and 30 kW sized engines to power the heat pump and total energy systems.

Pursuance of the above policies could have the following impact:

- o A substantial Stirling engine market may be formed in Japan since achieving stated goals could result in a market for Stirling engines in excess of 50,000 units per year with a capacity of approximately 500 MW.
- o Japanese industry could be provided with such a strong position in Stirling engine technology that by the mid 1980's efforts to use natural gas in a similar manner in the United States may well be based on Japanese technology.

APPENDIX A

GENERAL STIRLING ENGINE REFERENCES

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Detroit Diesel Allison Division of General Motors
Garrett Corporation
General Electric Gas Turbine Division
Cooper Energy Services
Waukesha Engine Division, Dresser Industries
Dresser Clark Division, Dresser Industries

Arthur D. Little's Data Base

This data base has been compiled within the past three years primarily by conducting a substantial number of in-person interviews with key Original Engine Manufacturers (OEMs) and engine manufacturers in each application area on a worldwide basis. The information obtained during these interviews was expanded and filled in through the study of trade publications, engine and equipment manufacturers' brochures, as well as engine catalogs such as those published in Automotive Industries and Diesel and Gas Turbine Progress. At present the data base includes the following engines and engine applications:

- Industrial equipment
- Marine (pleasure craft and light commercial)
- Agricultural equipment
- Lawn and garden equipment
- Compressors (portable)
- Passenger cars
- Trucks (light, medium, and heavy duty)

REFERENCES

ENGINE & APPLICATION DATA Cont'd.

- Welders
- Construction equipment
- Generator sets
- Mobile refrigeration equipment
- Light and experimental aircraft
- Natural gas pipeline engine applications
- Heat pumps

APPENDIX B

INDIVIDUALS AND ORGANIZATIONS IN STIRLING ENGINE TECHNOLOGY INTERVIEWED FOR THIS PROGRAM

INTERVIEWS WERE CONDUCTED WITH SEVERAL PERSONS AND ORGANIZATIONSACTVE IN THE STIRLING ENGINE FIELD. THESE CONTACTS INCLUDE:

DR. LARRY HOAGLAND, AMTECH, INC.
DR. KARL BASTRESS, DOE, WASHINGTON DC
MR. E. W. KITZNER, FORD MOTOR CO.
MR. E. AUXER, MR. J. A. BLEDSOE, GENERAL ELECTRIC
MR. F. HOEHN, MR. JACK STEARN, JPL
PROF. J. L. SMITH, JR., MIT
MR. BRUCE GOLDWATER, MTI
DR. DAVID A. DIDION, NBS
MR. ALEXANDER DANIELS, PHILPS LAB., NEW YORK
DR. THEODORE FINKELSTEIN, CONSULTANT
MR. L. WRIGHT, GAS RESEARCH INSTITUTE
DR. R. HOLTZ, ARGONNE NATIONAL LABORATORIES
MR. JAROSLAV WURM, INSTITUTE OF GAS TECHNOLOGY
MR. LENNART JOHANSSON, STIRLING POWER SYSTEMS CORP.

APPENDIX C.1

1980 GASOLINE ENGINE SALES BY APPLICATION

Based on data compiled by

Power Systems Research

1980 Gasoline Engine Sales by Application

Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Agricultural	Agricultural Tractors	40-55	306	100	Intl. Harv. C-153
	Balers	23-37	616	100	Wisconsin VG4D
	Combines	68	149	22	Chevrolet 250
		78	245	36	Intl. Harv. C-2
		95-98	191	28	Ford CSG649
			585	86	
	Irrigation Sets	73-78	5,404	28	Intl. Harv. C-221
		94-98	2,899	15	Chrysler H225
		126-136	2,965	16	Chrysler LH318
		178-189	3,250	17	Intl. Harv. C-54
		207-216	1,556	8	Intl. Harv. 537
			16,074	84	
	Swathers	73	621	24	Ford LSG633
		92-96	441	17	Chrysler H225
		102	1,035	39	AMC 258-16
		131	279	11	Chrysler LH-318
			2,376	91	
	Other Ag. Equipment	92-96	58	53	Ford LSG641
		208	43	39	Ford CSG888
			101	92	
Compressors	Compressor	3-7	4,566	24	Briggs & Stratton 243430
		10-12	5,729	30	Briggs & Stratton 326430
		23-39	3,255	17	Wisconsin VG4D
		50-75	2,620	14	Waukesha VRG155
		129-131	1,550	8	Ford CSG850
			17,720	93	

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1980 Gasoline Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Construction	Asphalt Pavers	57	38	44	Ford RSG428
		98	48	56	Ford CSG649
			86	100	
	Backhoes	45-55	629	59	Intl. Harv. C-153
		69-73	379	36	Ford LSG63[illegible]
		102	56	5	Intl. Harv. C-345
			1,064	100	
	Boring & Drill Rigs	1	169	31	McCulloch MAC110
		10-15	167	30	Wisconsin TJD
		75	92	17	White G2300
		98	65	12	Ford CSG649
		135	43	8	White G3400
			536	98	
	Cement & Mortar Mixers	2-3	21,416	43	Wisconsin EY-18-3W
		4	15,711	31	Wisconsin ACN
		5	11,605	23	Wisconsin BKN
		14	1,605	3	Caan CCKB
			50,337	100	
	Concrete Buggies	1-2	378	38	Clinton 492
		5-6	440	45	Briggs & Stratton 2334
		9	162	17	Wisconsin TRA-12
			980	100	
	Concrete Finishers	1	605	24	McCulloch MAC-130
		2-3	967	38	linton 415
		4	969	38	Wisconsin ACN
			2,541	100	

1980 Gasoline Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Construction	Concrete Vibrators	1	1,352	20	McCulloch MAC-110
		3	3,881	57	Briggs & Stratton 111200
		4	908	13	Kohler K141
		7	647	10	Kohler K301
			6,788	100	
	Cranes	98	87	84	Ford CSG649
		129	17	16	Ford RSG854
			104	100	
	Excavators	73	84	96	Ford LSG633
	Forest/Harvesting Equipment	98	0	0	Ford CSG649
	Graders	57-60	0	0	Ford RSG428 & RSG431
	Paving Equipment	14	152	41	Kohler K582
		35-37	99	27	Wisconsin VG4D
		47	84	23	Wisconsin V465
			335	91	
	Rollers & Compactors	7-12	1,718	30	Briggs & Stratton 401417
		14	1,536	27	Kohler K582
		98	956	17	Ford CSG649
			4,210	74	
	Rubber-tired Loaders	25-26	162	47	Continental R688-46
		96-98	171	50	Chrysler H225
			333	97	

1980 Gasoline Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Construction	Skid Steer Loaders	7	2,162	29	Kohler K321
		16	1,907	26	Onan NHC
		35-39	1,856	25	Ford KSG416
			5,925	80	
	Miscellaneous	131	430	100	Ford CSG850
General Industrial	AGG Crushing and Process Equipment	95-98	55	70	Ford CSG649
		215	17	22	Intl. Harv. 446
			72	92	
	Chippers	37	529	18	Wisconsin VG4D
		47-50	1,632	54	Wisconsin V-4650
		96-98	498	16	Ford CSG649
			2,659	88	
	Highway and Railroad Refrigeration	7-9	3,781	50	Kohler K321
		11-12	3,899	50	Onan CCKA
			7,680	100	
	Industrial Tractors	73	344	96	Ford LSG633
	Locomotives	98	31	100	Ford CSG649
	Oil Field Equipment	37	86	37	Wisconsin VG4D
		65-69	92	40	Intl. Harv. C-200
		112	36	16	Waukesha VRG310
			214	93	

1980 Gasoline Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

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Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
General Industrial	Pumps	1-2	29,079	35	Homelite 9TP3-1B
		3-4	27,464	33	Briggs & Stratton 130200
		5-9	10,716	13	Briggs & Stratton 170400
		10-15	10,033	12	Wisconsin AGND
			77,292	93	
	Scrubbers and Sweepers	6-7	1,421	33	Kohler K301
		12-23	1,250	29	Onan NHC
		35-39	392	9	Wisconsin VG4
		65	531	12	White G-1600
		96	346	8	Chrysler H225
		131	371	8	Chrysler LH318
			4,311	99	
Highway	Buses	133	3,721	75	Intl. Harv. MV404
		215	1,262	25	Intl. Harv. 446
			4,983	100	
Lawn & Garden	Chain saws	1	2,473,565	100	Homelite Sup XL Auto
	Lawn & Garden Tractors	2-5	473,895	47	Briggs & Stratton 170700
		6-10	432,586	43	Briggs & Stratton 190700
		11-15	95,096	9	Briggs & Stratton 401708
			1,001,577	99	
	Lawn Mowers	2	1,813,188	41	Tecumseh LAV-30-RA
		3	2,499,147	57	Briggs & Stratton 92500
			4,312,335	98	
	Mowers	3	1,532	47	Briggs & Stratton 111200
		5	1,515	47	Wisconsin EY-25
			3,047	94	

1980 Gasoline Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Lawn & Garden	Snow Blowers	1-2	550,758	51	Tecumseh H30
		3-4	242,582	22	Tecumseh HH50
		6-9	286,886	26	Tecumseh VM100
			1,080,276	99	
	Snowmobiles	12-15	63,954	63	Kohler K295-2AX
		17-22	33,365	33	Kohler K440-2AS
			97,319	99	
	Miscellaneous Lawn & Garden Equipment	1	17,256	47	Kioritz JP30
		3	19,813	53	Briggs & Stratton 100200
			37,069	100	
Marine - Commercial	Marine Light Commercial	105	0	0	AMC 304-V8
Marine - Pleasure	Marine Recreation	93-98	27,469	39	Chevrolet 350
		131	6,296	9	Chrysler LH318
		173-178	21,729	31	Chevrolet 454
			55,494	79	
Material Handling	Aerial Lifts	14	176	10	Kohler K528
		23	822	48	Wisconsin VH4D
		37-39	435	26	Wisconsin VG4D
		60	265	16	Ford BSG333
			1,698	100	
	Fork Lifts	38-41	17,712	26	Continental F-135
		50-53	15,031	27	Toyota JP2.2
		65-75	13,511	24	Nissan JP2.0
			43,254	77	

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1980 Gasoline Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Material Handling	Other Equipment	26	349	68	Continental R638-46
		41	161	32	Continental 2145
			510	100	
Welders/ Generators	Generator Sets (see attached sheet)	1-5	99,364	30	Clinton 412
		6-10	121,827	37	Briggs & Stratton 190400
		11-15	98,113	30	Briggs & Stratton 326430
			319,304	97	
	Light Plants	1	498	28	Clinton 401
		3-4	625	36	Kohler K141
		7-9	628	36	Onan CCK
			1,451	100	
Other	Dist. Loose	3	273,890	73	Briggs & Stratton 92500
		4	47,262	12	Briggs & Stratton 130900
			321,152	85	
	Exports	3	1,397,354	51	Briggs & Stratton 100200
		5-7	977,951	36	Briggs & Stratton 190400
			2,375,305	87	
	Mil/Veh/EQ (Tactical Military Vehicles?)	72	1,036	50	Continental F-245
		75	1,043	50	White 92300
			2,079	100	

APPENDIX C.2

1980 DIESEL ENGINE SALES BY APPLICATION

Based upon data compiled by

Power Systems Research

1980 Diesel Engine Sales by Application
Based upon Horsepower Fating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine	
Agricultural	Agricultural Tractors	62.5-82.5	38,632	20.6	Deere (US)	4276D
		97.5-107.5	26,497	14.1	Deere (US)	6329D
		127.5-147.5	32,545	11.3	Int. Harv. (WG)	DT-358
			97,674	52.0		
	Balers (1979) (No. Sales in 1980)	53	86	38.9	Int. Harv (WG)	D-179
		68	62	28.0	Deere (US)	4219D
		98	73	33.0	Deere (US)	4276T
	Combines	90-102	4,886	20.8	AC (US)	433T
		130-138	5,932	25.3	Deere (US)	6466D
		162-175	7,389	31.5	Deere (US)	6466T
		253	2,504	10.7	Deere (US)	6466A
			20,711	88.3		
	Irrigation Sets	28-37	1,260	14.3	Lister (UK)	ST3
		61-71	1,627	18.5	Deere (FR)	4239D
		83-90	1,501	17.1	Cat. (US)	3304
		99-110	983	11.2	White (US)	D3400
		155-163	755	8.6	Int. Har. (US)	DT436
		231-253	720	8.2	Det. Diesel (US)	6-71
			6,846	77.9		
	Miscellaneous Agricultural Equipment	11	80	17.6	Petters (UK)	PJ1
		16	84	18.5	Petters (UK)	PH2
		29	49	10.8	Volvo (SW)	MD17CHD
		65-68	226	49.7	White (US)	D2000
			439	96.6		
	Mowers	68	306	100.0	White (US)	D2000
			306	100.0		

1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine	
Agricultural	Sprayers	68-73	398	59.0	Deere (US)	4276D
		83-99	258	38.3	Cummins (US)	
			656	97.3		
	Swathers	53-65	924	22.3	Int. Harv. (WG)	D206
		71-79	1,818	43.9	Deere (FR)	4239D
		90	371	9.0	Int. Harv. (US)	D312
		106	943	22.8	Deere (US)	6359D
			4,056	98.C		
Compressors	Compressors	62.5-87.5	7,050	40.1	Deere (US)	4219D
		97.5-102.5	1,861	10.6	Deere (US)	4276T
		127.5-142.5	2,297	13.1	Det.Dies (US)	4-53
		157.5-162.5	1,481	8.4	Deere (US)	6466T
		177.5-187.5	961	5.5	Det.Dies (US)	4-71
			13,650	77.7		
Construction	Asphalt Pavers	76-83	581	33.8	Det.Dies (US)	3-53
		132-135	600	34.9	Det.Dies (US)	4-53
			1,181	68.7		
	Boring & Drill Rigs	9-19	144	24.5	Yanmar (JP)	TS105
		26-39	102	17.3	Lister (UK)	HRW2
		68	86	14.6	White (US)	D2000
		95-110	124	21.2	White (US)	D3400
			438	77.5		
	Backhoes	52-56	5,680	30.5	Deere (US)	3164D
		65-71	8,396	45.2	Deere (FR)	4239D
			14,076	75.7		

1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine	
Construction	Concrete Vibrators	6	126	81.8	Lister (UK)	8-1
		15	28	18.2	Hatz (WG)	E950
			254	100.0		
	Miscellaneous	132	108	27.9	Det.Dies (US)	4-53
		241	122	31.5	Cummins (US)	NT-855C
		262	88	22.7	Det.Dies (US)	6-71T
			318	82.1		
	Cranes	85-99	962	12.8	Cummins (UK)	V-378C
		132-137	1,513	20.2	Det.Dies (US)	4-53
		168-186	2,089	27.8	Cummins (UK)	V-504C
		203	1,305	17.4	Det.Dies (US)	6V-53
			5,869	78.2		
	Crawler Tractors	65-68	4,237	18.6	Deere (US)	4219D
		83-98	5,328	23.4	Cat (US)	3304
		147-162	4,604	20.2	Cat (US)	3306T
		182-193	2,647	11.6	Int. Harv. (US)	DT-466B
		208-233	1,903	8.3	Det.Dies (US)	64-71B
			18,719	82.1		
	Excavators	132-135	1,590	26.2	Cat. (US)	3208
		283	903	14.8	Deere (US)	6619A
		168-186	999	16.4	Det.Dies (US)	4-71
		302-320	501	8.2	Cummins (US)	VT-903
		85-90	504	8.3	Cat. (US)	3304
			4,497	73.9		
	Forest Harvesting Equipment	47-53	168	21.4	Int. Harv. (WG)	D-179
		76	103	13.1	Perkins (US)	4.236
		122	85	10.8	Case (US)	336BDT
		258-266	151	19.2	Det.Dies (US)	8V-71TT
		313-320	167	21.2	Cummins (US)	NTA-85
			674	85.7		

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1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine	
Construction	Graders	68-76	784	15.2	Deere (US)	4219D
		85	975	18.9	Cat (US)	3304
		147-162	1,621	31.4	Deere (US)	6414T
		251-262	1,107	21.4	Det.Dies (US)	6-71
			4,487	86.9		
	Mining Miscellaneous	53-68	932	21.8	Deutz (WG)	F4L912W
		135-150	474	11.1	Cat. (US)	3208
		162-186	589	13.8	Det.Dies (US)	4-71
		229-238	666	15.6	Cummins (US)	NH-230
		306-313	322	7.6	Cummins (US)	NTA-855
		351	307	7.2	Det.Dies (US)	8V-92
			3,290	77.1		
	Off-highway Trucks	218	607	13.1	Cummins (US)	NTA-230
		251-262	755	16.3	Cat. (US)	3306T
		295-314	1,132	24.4	Cummins (US)	NTA-855
		330	284	6.1	Int. Harv. (US)	DT-817C
		502-504	466	10.0	Cat. (US)	3408TA
		522-703	791	17.0	Cat. (US)	3412T
			4,035	86.9		
	Paving Equipment	68	608	30.0	Deere (US)	4219D
		83-85	374	18.4	Det.Dies (US)	3-53
		132-135	503	24.8	Det.Dies (US)	4-53
		221	147	7.2	Det.Dies (US)	68-71
			1,632	80.4		
	Rubber-Tired Dozers	162	275	25.6	Cat. (US)	3306
		241-262	449	41.8	Cummins (US)	NT-855C
		305	149	13.9	Det.Dies (US)	8V-71
			873	81.3		

1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine	
Construction	Rubber-Tired	65-76	4,134	19.7	Deere (US)	4219D
	Loaders	79-85	2,356	11.2	Cat. (US)	3304
		146-162	4,447	21.2	Cat. (US)	3306
	(Wide Distr.)	243-262	3,721	17.7	Cat. (US)	3306T
		313-330	945	4.5	Cummins (US)	NTA 885
			15,603	74.3		
	Rollers and	19-27	1,161	15.0	Hatz (WG)	2790
	Compactors	60-76	1,586	20.4	Deere (US)	4219D
		83	1,505	19.4	Det.Dies. (US)	3-53
		122-123	390	5.0	Deere (US)	6414D
		132-139	1,058	13.6	Det. Dies (US)	4-53
			5,700	73.4		
	Skid Steer	8	2,300	21.5	Jubota (JP)	ZB600-1-B
	Loaders	20	2,339	21.9	Deutz (WG)	F2L511D
		35-37	3,410	32.8	Perkins (UK)	4.108
		56-60	563	5.3	Case (US)	G188D
	Scrapers	135	436	16.6	Cat. (US)	3208
		162-168	593	22.6	Cummins (UK)	V-504C
		258-162	372	14.2	Det. Diesel (US)	6.71T
		283-295	360	13.7	Deere (US)	6619A
		302-313	432	16.4	Cummins (US)	NTA-855
			2,193	83.5		
	Skidders	85-100	1,115	25.1	Case (US)	A336
		121-132	1,445	32.5	Deere (US)	6414D
		231	761	17.1	Cummins (US)	NH-230V
			3,321	74.7		
	Tampers	6-7	190	64.2	Lister (UK)	8-1
		15	106	35.8	Hatz (WG)	E950
			296	100.0		

1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine	
Construction	Trenches	20-31	773	13.0	Deutz (WG)	F2L912
		51-56	874	14.7	Case (US)	9188D
		60-68	868	14.6	Deere (US)	4219D
		83-85	1,133	19.0	Det. Dies. (US)	3-53
		132-139	189	19.9	Cat. (US)	3208
			4,837	81.2		
General Industrial	Chippers	67-68	86	23.6	Deere (US)	4219D
		75-85	53	14.5	Cat. (US)	3304
		132	91	24.9	Det. Dies (US)	4-53
		251	81	22.2	Det. Dies (US)	6-71
			311	85.2		
	Crushing & Proc. Equipment	83-85	257	32.9	Det. Dies (US)	3-53
		101-110	120	15.4	Waukesha (US)	VRD 310
		135-146	145	18.6	Cat. (US)	3208
			522	66.9		
	Industrial Tractors	35-37	876	11.1	Perkins (UK)	4.108
		56-57	1,150	14.6	Case (US)	G188D
		65-68	2,784	35.2	Deere (US)	4219D
		75-76	1,522	19.2	Ford (UK)	BSD442
		90-92	1,199	15.2	AC (US)	433T
			7,531	94.5		
	Locomotive	85	88	27.3	Cat. (US)	3304
		168	74	23.0	Cummins (UK)	V-504
		368	84	26.1	Cummins (US)	NTC-400
		419	58	18.0	Cummins (US)	KT-450
		435	18	5.6	Cat. (US)	D379
			322	100.0		

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1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine	
General Industrial	Oil Field Equipment	18-20	632	9.5	Lister (UK)	ST2
		28-45	929	14.0	Lister (UK)	ST3
		65-83	797	12.0	Det. Dies (US)	3.53
		95-103	827	12.5	Deutz (WG)	F6L912
		129-137	1,132	17.1	Det. Dies (US)	4-53
		302-308	602	9.1	Det. Dies (US)	8V-71
		503	437	6.6	Cat. (US)	3412T
			5,356	80.8		
	Pumps	2.5-7.5	726	5.7	Lister (UK)	8-1
		7.5-17.5	1,740	13.6	Lumbardini (IT)	710
		17.5-27.5	1,855	14.5	Lumbardini (IT)	914
	(Wide Distr.)	27.5-42.5	1,961	15.3	Lister (UK)	HR3
		82.5-102.5	1,496	11.7	Cat. (US)	3304
		127.5-147.5	1,667	13.0	Cat. (US)	3208
			9,445	73.8		
	Scrubbers and Sweepers	26-35	245	11.3	Onan (US)	RDJF
		132-135	1,042	48.3	Cat. (US)	3208
		185	241	11.2	Cummins (UK)	V-555
		203	423	19.6	Det. Dies (US)	6V-53
			1,951	90.4		
	Highway & Railroad Refrigeration	26-37	4,144	19.3	Perkins (UK)	4.108
		49	15,160	70.6	Isuzu (JP)	C240
Highway	Buses	135	852	15.4	Cat. (US)	3208
		162	931	16.8	Int. Harv. (US)	DT-466
		203	1,066	19.3	Det. Dies. (US)	6V-53
		262	605	10.9	Det. Dies. (US)	8V-71TTA
		305	1,435	26.0	Det. Dies. (US)	8V-71
			4,889	88.4		

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1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Highway	Cars	36-39	129,500	33.2	Volks (WG) 068.2
		49-53	39,369	10.1	Mer.B.(WG) OM616/5
		86-89	220,610	56.6	Olds (US) 5.7 L
			389,480	100	
	Trucks Classes 1 & 2	36	17,570	22.7	Volks (WG) 068.2
		65-67	7,375	9.5	Nissan (JP) SD33
		89	52,560	67.8	Olds (US) 5.7 L
			77,505	100	
	Trucks Classes 3 & 4	156	3,319	100	Det. Diesel (US) 4-53T
	Trucks Class 5	102	1,056	88	Perkins (US) 6.354
		162	144	12	Intl. Harv.(US) DT-466
			1,200	100	
	Trucks Class 6	121-129	2,994	8.2	Merc. Benz (WG) OM352A
		131-135	25,368	69.3	Det. Diesel(US) 8.2 L
		162-168	2,823	7.7	Merc. Benz (WG) OM355/5
			31,185	85.2	
	Trucks Class 7	135	8,970	24.9	Cat. (US) 3208
		152-162	18,405	51.1	Intl. Harv.(US) DT-466
		251	4,246	11.8	Det. Diesel(US) 6-71
			31,621	87.8	
	Trucks Class 8	230-231	20,604	17.1	Cummins (US) Formula 290
		262-266	13,051	10.8	Det. Diesel(US) 6V-9 TTA
		281-292	34,993	29.1	Mack (US) ET-673E
		302-320	21,077	17.5	Det. Diesel(US) 8V-92 TTA
		415-419	9,554	7.9	Det. Diesel(US) 8V-92 TA
			99,279	82.4	

1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Lawn & Garden	Lawn & Garden Tractors	6-8	6,719	24.3	Kubota (JP) ZB500C-1-B
		9-11	8,848	32.0	Kubota (JP) D650-B
		13-15	9,326	53.7	Yanmar (JP) TS155
		16-18	2,767	10.0	Kubota (JP) DH1101-B
			27,660	100	
Marine - Commercial	Marine - Commercial	82.5-102.5	449	10.9	Cummins (UK) V-378-C
		147.5-162.5	559	13.6	Cat. (US) 3306T
		202.5-212.5	509	12.4	Det.Diesel (US) 6V-53
		227.5-232.5	377	9.2	AC (US) 685T
		247.5-267.5	528	12.8	Det.Diesel (US) 6-71
		267.5-302.5	370	9.0	Cat. (US) 3406T
		502.5-507.5	241	5.8	Cat. (US) 3408TA
			3,033	73.6	
Marine - Pleasure	Marine/Rec.	7.5-17.5	3,481	26.2	Yanmar (JP) 2T90LE
		17.5-27.5	1,932	14.5	Peugeot (FR) U28
		27.5-37.5	1,793	13.5	Perkins (UK) 4.108
		127.5-147.5	2,615	19.7	Perkins (US) T6.354
			9,821	73.9	
Material Handling	Aerial Lifts	15	193	47	Hatz (WG) E950
		26	221	53	Hatz (WG) Z790
			414	100	
	Fork Lifts	26-37	1,869	12.6	Waukesha (US) VRD155
		51-65	2,413	16.2	Perkins (UK) 4.203
		67-76	5,032	33.8	Perkins (US) 4.236
		80-85	1,137	7.6	Toyota (JP) 2P
		92-102	1,835	12.3	Perkins (US) 6.354
		122-135	1,534	10.3	Case (US) 336BDT
			13,820	92.8	

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1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Material Handling	Terminal Tractors	129-135	1,029	80.8	Cat. (US) 3208
		185-203	245	19.2	Cummins (UK) V-555
			1,274	100	
	Tow Tractors	37	108	22.0	Waukesha (US) VRD155
		129-135	276	56.2	Intl. Harv. (US) D-466
		185	62	12.6	Cummins (UK) V-555
			446	90.8	
	Other	53-68	182	26.3	Intl. Harv. (WG) D-179
		83-92	106	15.3	White (US) D-3000
		129-135	226	32.6	Cat. (US) 3208
		168-186	98	14.1	Cummins (UK) Y-504-C
			612	88.3	
Welders/ Generators	Generator Sets	2.5-12.5	3,070	6.8	Onan (US) DJA
		12.5-22.5	4,394	9.7	Onan (US) RDJE
		27.5-37.5	5,883	13.0	Onan (US) RDJE
		82.5-92.5	3,659	8.1	Cat. (US) 3304T
	(Wide Distribution)	127.5-137.5	2,111	4.6	Cat. (US) 3208
		157.5-167.5	2,216	4.9	Intl. Harv. (US) DT-436
		167.5-177.5	1,879	4.1	Cat. (US) 3304T
		247.5-262.5	4,174	9.2	Cat. (US) 3306T
		457.5-462.5	2,267	5.0	Cummins (US) KTA-1150
			29,653	65.4	
	Light Plants	14-15	648	28.2	Onan (US) DJBA
		35	814	35.4	Onan (US) RDJF
		85-92	501	21.8	White (US) D-3000
			1,963	85.4	

1980 Diesel Engine Sales by Application
Based upon Horsepower Rating at 2400 rpm (1-750 hp)

Market Segment	Application	HP Range	Sales	% of Total	Sales Leading Engine
Welders/ Generators	Welders	35-39	3,490	17.3	Waukesha (US) VRD155
		45-56	8,021	39.8	Perkins (UK) D3.152
		63-76	3,303	16.4	Perkins (US) 4.236
		83-95	1,202	6.0	Cat. (US) 3304
			16,016	79.5	
Other	Dist. Repr. and Loose Eng. Exp. (see graph)	27.5-57.5	4,862	10.2	Deere (US) 3164D
		62.5-77.5	3,956	8.3	Deere (US) 4219D
		82.5-107.5	7,377	15.5	Det. Diesel (US) 3-53
		127.5-147.5	3,706	7.8	Cat. (US) 3208
		157.5-167.5	3,742	7.9	Cat. (US) 3306T
		227.5-232.5	2,569	5.4	Cummins (US) NH-230
		277.5-292.5	4,679	9.8	Cummins (US) Formula 250
		297.5-317.5	5,626	11.8	Cummins (US) NTC-290
			36,517	76.7	
	Exports	68-76	3,889	9.3	Deere (US) 4219D
		83-101	3,772	9.0	Cat. (US) 3304
		129-138	9,602	23.1	Cat. (US) 3208
		228-231	4,272	10.3	Cummins (US) 6V-71
		302-313	4,994	12.0	Cummins (US) NTA-855
			26,529	63.7	
	Military Vehicles	132-135	1,179	17.8	Det. Diesel (US) 4-53
		203	3,972	59.9	Det. Diesel (US) 6V-53
			5,151	77.7	

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APPENDIX C-3

MEDIUM AND LOW SPEED DIESEL, GAS TURBINE, AND RANKINE ENGINE PERFORMANCE AND COST

CHARACTERISTICS OF TYPICAL MEDIUM SPEED DIESELS UP TO 3,750 kW (5,000 HP)

Manufacturer	ALCO Power Inc.	Colt-Fairbanks Morse	Enterprise-Delaval	General Motors Electromotive	MAN AG	Mirrlees Blackstone Limited	Cooper Energy Services - Superior Products			Waukesha Engine Division Dresser
Model	6F251	38TD	DSR	645	40/45	KV	40	G-825	GTL-825	VHP
Speed	1200	900	450	900	600	600	900	900	900	1200
Emissions g/kW hr HC CO NO_x	8.8	0.0 1.3 13.0	11.8	NA	13.0	13.9	9.11	- - 8.7	1.5 1.1 11.3*	NA
Efficiency %	36	34	36	34	39	37	34	29	32	36
Coolant Type kg/hr	Water	Water	Water	Water	Water	Water	Water	Water	Water	Water
Cost $/kW	157	250	349	177	268	244	261	322	294	155
Weight kg/kW	8.4	10.6	20.1	6.4	17.0	16.4	15.2	16	13	9.4
Size m^3/kW	.015	.015	.011	.027	.023	.019	.011	.030	.030	.017

(Continued)

Manufacturer		ALCO Power Inc.	Colt-Fairbanks Morse	Enterprise Delaval	General Motors Electromotive	MAN AG	Mirrlees Blackstone Limited	Cooper Energy Services - Superior Products			Waukesha Engine Division Dresser
Model		6F251	38TD	DSR	645	40/45	KV	40	G-825	GTL-825	VHP
Power Range	kW	2090 2760	1480 2955	3600 8950	1075 3600	3360 10070	1790 8950	540 720	447 895	619 1640	305 1205
	hp	2800 3730	1980 3960	4827 12000	1440 4830	4500 13500	2400 12000	720 960	600 1200	830 2200	411 1617
Additional Data Figure Numbers											
Use*		I,M,L	I,M,L	I,M	I,M,L	I,M	I,M	I,M	I	I	I,M

*I = Industrial Drive
M = Marine
L = Locomotive

Source: Arthur D. Little, Inc.

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CHARACTERISTICS OF TYPICAL SLOW SPEED ENGINES UP TO 3,730 kW (5,000 HP)

Manufacturer	Cooper Energy Services Inc.	Cooper Energy Services Inc.	Cooper Energy Services Inc.	Dresser Clark	Enterprise Delaval	Ingersoll Rand	MAN AC	Sulzer Bros. Ltd.
Model	GMVH	LSV	W-330	HBA-T	HVI 2C4	KVR	40/54	TAF 48
Speed RPM	330	400	330	300	600	350	450	257
Emissions HC g/kW hr		.4	3.9			2.3*		
Emissions CO g/kW hr		7.4	1.1			1.3*		
Emissions NO_x g/kW hr	2.7*	13	6.7	8.4*	15.8*	27.0*		
Efficiency %	34*	37	37	30*	31*	33*	41	38 (est)
Coolant Type Flow l/min	Water ≈5000	Water 8300	Water NA	Water NA	Water NA	Water NA	Water NA	Water NA
Cost $/kW	335	370	370	400	496	500	Not Available	
Weight kg/kW	46	24-40	30	50	18	41	Not Avail.	37
Size m^3/kW	.095	.038	.042	.099	.034	.080	Not Available	
Power Range kW	1007-2013	2240-5590	2983-5966	970-1940	1120-3730	2088-4176	2430-7300	3940
Power Range hp	1350-2700	3000-7500	4000-8000	1300-2600	1500-5000	2800-5600	3260-9800	5280
Additional Data Figure Numbers		6-8						
Use	G	I,M		G		G	I,M	I,M

Use Key

I = Industrial Drive
M = Marine
G = Pipeline Pumping

*Clean burn configuration.

Source: Arthur D. Little, Inc.

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CHARACTERISTICS OF TYPICAL NON-AIRCRAFT GAS TURBINES UNDER 3,730 kW (5,000 HP)

Manufacturer	Avco-Lycoming			Detroit Diesel Allison Division of General Motors				Garrett Div. Airesearch		Pratt & Whitney Aircraft of Canada				Solar Gas Turbine Div. International Harvester		
Model	Super TF-25	TC-35	Super TF-40	501KB	501KF	GT404	GT505	IE831-800	ME831-800	ST6 J70	ST6 J77	ST6 K77	ST6 776	Titan	Saturn	Centaur
Emissions* HC CO kW/hr NO_x	.02-.03[2] 2.0 11.2-12.2	Not Avail.	.22-.03[2] 2.5 8.8-8.5	2,4 .045 1.27 10				Not Available		.194 .174 3.2 Representative of entire P&W line						
Efficiency %	22	22	24	24	25	29	28	19	13	19	20	21	21	14	20	22
Coolant Type Flow kg/sec	Air 10.0	Air 10.9	Air 11.3	Air 15.4	Air 15.0	Air 1.6	Air 2.0	Air 3.6	Air 3.6	Air 2.7	Air 2.7	Air 2.7	Air 5.9	Air 1.3	Air 5.9	Air 17.2
Cost $/kW	≈$285	177-247	248-270	126	198	Not Available (3)		155	280	328[1]	341[1]	286[1]	279[1]	915	-	-
Weight kg/kW	.40	.32	.27	.17	.35	3.6	2.8	1.5	2.5	.42	.42	.28	.31	.56	8.9	7.2
Size $(m^3/kW)x10^{-4}$	6.9	5.9	4.4	3.2	3.2	37.8	29.2	19.7	44.7	14.9	13.8	9.2	18.9	.13	25	15.8
Power Range kW	1700	2400	2700	3120	3230	225	290	515	285	380	410	490	1074	71	800	2700
Power Range hp	2280	3220	3620	4184	4330	300	390	690	382	510	550	660	1440	95	1075	3620
Additional Data Figure Numbers				6-17 6-18	6-18									6-20		
Use	I,E,M	E	I,M,E	I,E	M	I	I	I,E	E	E,M	E,M	M	M	E	I,E	I,E

Use Key

I = Industrial
M = Marine
E = Electric Power Generation
[1]With reduction gear box (to 2200 RPM)

* at full power
2) kerosense (JP-4, JP-5, Set A, Jc+B) and Diesel fuel (D-2) or D-4) respectively
3) military engines only
4) kg/hr

Source: Arthur D. Little, Inc.

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TECHNICAL CHARACTERISTICS FOR AVAILABLE RANKINE CYCLE SYSTEMS (HIGH TEMPERATURE)

System Characteristics	Sundstrand (Toluene)	Thermo-Electron (Fluorinol)	Peterbrotherhood/ Thermo-Electron (Steam)
1. Size	600 KW	440 KW	1 - 15 MW
2. Source Temperature	600^0F - 800^0F	500^0F - 700^0F	600^0F^+
3. Condenser Temperature	60^0F	60^0F	60^0
4. Source Medium	Exhaust Gas	Exhaust Gas	Exhaust Gas
5. Status	Commercial	Development	Commercial
6. No. of Operating Units	4	0	130
7. System Type	Simple Cycle	Simple Cycle	Simple Cycle
8. Working Fluid	Toluene	Fluorinol-85	Steam
9. Safety Problems	Toxic, Flamm.	Toxic, Flamm.	None
10. Reliability	3 Years Oper.		20 Years Oper.
11. Primary Application	Municipal Plant		Municipal Plant Industry

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TECHNICAL CHARACTERISTICS FOR FREON CYCLE SYSTEMS (LOW TEMPEPATURE)

System Characteristics	Barber Nichols	IHI (Japan)
1. Size	500 KW	490 KW
2. Source Temperature	340°F	260°F
3. Condenser Temperature	60°F	
4. Source Medium	Geothermal Brine	
5. Status	Demonstration	Commercial
6. No. of Operating Units	1	
7. System Type	Direct Contact Boiler System	Simple Cycle
8. Working Fluid	Isobutane	R-11
9. Safety Problems		Negligible
10. Primary Application	Geothermal	Industrial Waste Heat

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COST RANGE OF RANKINE CYCLE ENGINE SYSTEMS

SYSTEM	CAPACITY	INSTALLED COST
TECO/Peter Brotherhood (Waste heat steam power system)	500 to 15,000 KW	$500-800/KW
TECO (Truck diesel engine bottoming ORC)	36 HP	$2500-6000/Unit
SUNSTRAND (Waste heat ORC system)	900 to 1125 HP 600 to 750 KW	$700-800/KW
MTI (ORC, Binary and Steam systems)	500 to 2000 KW (ORC & Binary) 1000 to 4000 KW (Steam)	$900-1300/KW
BIPHASE (Two-phase turbine)	100 to 600 KW	$200-600/KW
RPA REPORT - 1978 (ORC Units)	Variable	$800-1400/KW

APPENDIX D

CLUSTER ANALYSIS RESULTS SUMMARY

CLASSIFICATION OF APPLICATIONS BY CLUSTER ANALYSIS

As discussed in Chapter 4, it was necessary to reduce the great number of applications down to a small number of application classes. This was done in a manner which grouped applications with similar needs for certain engine characteristics together. Because engines usually serve a broad number of applications, it was deemed reasonable that applications could be so grouped that each group, or application class, could have its engine needs met by one engine type.

To group applications together solely on the basis of the engines presently used, however, would serve to exclude completely non-conventional applications in which no engines are presently used. Instead, a methodology was needed which would cluster applications together in groups by the engine needs or desired engine characteristics of the individual applications.

An objective clustering technique known as Cluster Analysis was utilized to determine the groups of applications which would be known as "application classes."

Hierarchical Clustering

Hierarchical clustering is a method of data classification which objectively arranges any set of individual items into progessively larger and less similar groupings based on the numerical observations of characteristics (in this case, engine needs) associated with each application. Known as clusters, these groupings are then depicted in a tree diagram, or dendrogram, which displays the genealogy of their formulation. For each of the applications to be grouped, a set of observations for characteristics of the application is obtained. (See Table D-1, discussed below.) The classification is based upon the similarity of the observations as measured by the squared Euclidean distance between the observations in each possible pair of applications. Whenever two applications are judged most similar because they are separated by the shortest distance; they are merged into a cluster. This cluster is treated as a single application class. This distance from that cluster to any other application is then computed and the process repeated until all the applications with similar characteristics are merged into a single cluster or application class.

While this can be done by hand with a small number of applications and characteristics, our analysis has 12 characteristics and about 80 applications. Therefore, a computer program developed in 1976 by Michael Grossman and Theodore Glickman was utilized.

Table D-1 provided the inputs to the cluster analysis. Each major application is listed on the vertical. The engine needs or characteristics

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which could be important to an application are listed horizontally. The first seven columns are those engine characteristics which are assumed to be inherent in a Stirling Engine. The last five columns represent areas where present Stirling technology needs development work to make the engine equal to conventional engines. All other engine characteristics were assumed to be prerequisities for all applications, and not a means of distinguishing between applications.

It is recognized that other desired characteristics or operational factors such as reliability, duty cycle, parts and service availability, torque back-up etc. are also used in selecting engines. However, these factors are much more a function of engine design, materials, cost and infrastructure trade-offs then they are inherent in any particular thermodynamic cycle, be it Otto, Stirling, Rankine, etc. The characteristics in Table D-1, then, are those used to select inherent engine characteristics rather then design features which can be built into almost any engine (for a price).

The relative importance of each characteristic to each application was then determined and "scored." The scoring system used was an arbitrary scale of 0 to 10. The higher the score, the more important the characteristic is to a particular application. For example, the ability to recover heat from an agricultural tractor is judged to be unimportant, and Heat Recovery receives a score of 0 for that application. However, heat recovery is very important to heat pumps using engine coolant as a source. In this case, heat recovery receives a 9. Only when a characteristic was absolutely essential to an application was a score of 10 assessed. Arthur D. Little professional staff with a thorough understanding of each application scored each application.

The cluster analysis technique then used the individual scores for each application to compute the euclidian distances between the applications. For the purposes of the cluster analysis, only the Stirling attributes were used (first seven columns). The results of this analysis are presented in Chapter 4.

In the cluster analysis program, the relative importance of the characteristics which influence clustering are determined. In this instance, the rank ordering and relative importance of the factors which influenced the clusters are:

Characteristic	Importance relative to other characteristics
Ability to switch fuels	741
Efficiency	374
Noise & vibration	341
Emissions	266
Heat recovery	156
Extended Maintenance Intervals	13
Long life	1

For example, the ability to switch fuels was 741 times more important than long life in determining application clusters. Extended maintenance intervals and long life were one and two orders of magnitude, respectively, less influenc'] in determining clustering than the other characteristics.

This analysis indicate that, since fuel switching was at levels twice as important as other characteristics, only two major application clusters need to be established: those in which fuel switches is important, and those in which it is not. For this study, however, ten different classes were created. They appear in Table 4.1.

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RELATIVE IMPORTANCE OF SELECTED ENGINE
CHARACTERISTICS FOR VARIOUS APPLICATIONS

Application No.	Applications	Ability to Switch Fuels	Emissions	Efficiency	Noise & Vibration	Heat Recovery	Extended Maintenance Interval	Long Life	Startability	Engine Cost	Engine Weight	Engine Physical Size	Load Following
1	Steady Load Isotope Powered Elect. Gen./Ground	0	0	10	9	0	9	9	1	1	5	5	2
2	Short-term Underwater Plant (essentially station)	3	0	9	8	5	2	0	1	2	6	7	3
3	Munic. Pwr. Gen. Using Waste/baseload	10	8	8	5	5	5	8	1	5	0	0	5
4	Pwr. Gen. from Low-grade Fuel/baseload	10	8	8	5	6	5	8	1	5	0	0	5
5	Space Heating & Cooling Appl.	6	9	3	7	6	6	7	0	7	6	6	3
6	Heat Pump for Resid. Appl.	6	9	8	9	7	7	8	1	8	5	6	6
7	Heat Pump for Comm. Appl.	8	5	9	5	8	8	9	1	6	3	3	4
8	Industrial Ht. Pump	7	4	9	4	8	8	9	1	6	2	2	3
9	Heart Pump	0	10	10	10	0	10	10	10	0	10	10	10
10	Wheelchair	7	9	9	9	0	8	7	0	2	9	9	9
11	Port. Refrig. for Bio. Samples	7	8	8	7	0	7	7	0	3	8	8	5
12	Vent. Fans in Remote Area	8	8	7	7	0	4	6	1	6	7	7	2
13	TV/Radio Power Source	7	5	7	7	0	5	6	1	6	6	4	2
14	Wood Splitter Using Wood	0	5	6	3	0	5	8	1	5	2	2	7
15	Back-Pack Power Plant	0	8	7	10	0	7	6	0	6	9	8	2
16	Third World Pwr. Gen (rice husk)/Gen. Purpose	10	2	5	2	0	6	6	0	6	6	4	8
17	Quiet Motorcycle/Moped	0	5	6	8	0	4	5	5	7	8	8	7
18	Tot. Energy/Pleasure Boats	2	8	5	8	8	4	5	5	3	6	7	6
19	Hybrid Elect. Vehicles	3	7	6	7	0	5	5	5	6	8	7	8
20	Car for Shoppers	5	8	7	7	0	5	5	5	7	8	8	9
21	Vehicle with Reg. Braking	5	6	7	7	0	5	6	5	7	8	8	7
22	Quiet Air Hammer to Brk. Conc.	0	5	5	8	0	4	7	0	5	4	5	8
23	Submersibles - Offshore Expl.	3	0	8	8	8	5	4	1	2	8	9	6
24	Undersea Mining	3	3	9	5	8	5	5	1	1	7	8	6
25	Heat Pump Using Coolant Source (Tot. Energy Sys.)	5	5	7	5	9	6	6	0	5	5	5	5
26	Hi Temp. Waste Heat - Pwr. Gen. (steady)	0	0	5	3	0	5	7	0	5	3	2	2
27	Indust. Process Appl.	0	5	7	4	7	7	8	1	5	2	5	5
28	Submarine/Gen. Purpose	3	2	8	7	7	2	3	0	3	8	8	5
29	Small Research Submarine	2	0	8	8	8	2	2	0	2	8	9	6
30	Large Military Sub	5	3	9	3	9	5	6	5	0	7	7	5
31	Unattended Surveillance Dev./Sub	2	0	8	10	0	4	6	5	2	8	9	3
32	Dish Mounted Sol. Thermal Pwr. Gen.	0	0	9	5	0	5	7	0	6	6	5	2
33	Solar Powered Pumps	0	0	8	5	0	5	7	1	6	6	5	2
34	Solar Powered Compressor/Shopair	0	0	8	5	0	5	7	1	6	6	5	2
35	Solar Power Lin. Alt.	0	0	8	5	0	5	7	1	6	6	5	2

	Applications	Ability to Switch Fuels	Emissions	Efficiency	Noise & Vibration	Heat Recovery	Extended Maintenance Interval	Long Life	Startability	Engine Cost	Engine Weight	Engine Physical Size	Load Following
38	Agriculture/Tractors	2	2	7	5	0	5	5	2	7	3	6	8
39	Selfpowered Eq.	2	2	7	2	0	5	5	2	5	5	5	5
40	Irrig. Pumps	2	2	9	2	0	8	7	2	7	2	1	3
41	Compressors/Consumer	2	2	2	5	0	2	2	4	8	5	5	2
42	Construction	2	5	6	8	0	2	7	4	8	2	6	2
43	Gas Pipeline	0	8	9	5	0	6	9	4	7	2	2	2
44	Oil, Gas Gathering	9	2	5	5	0	5	8	4	5	5	2	2
45	Construction Equip.	2	5	7	7	0	5	5	1	7	5	7	8
46	Generators/Portable	2	2	2	7	0	3	3	5	8	7	5	6
47	Emergency	0	1	3	4	2	4	4	9	5	3	5	8
48	Remote	2	2	9	3	2	9	9	5	5	3	3	6
49	Peaking Recip.	3	7	9	6	1	5	5	2	5	2	3	9
50	Ind. Equip//Indoors	4	9	7	7	0	2	7	4	5	2	6	5
51	Outdoors	2	5	7	7	0	2	7	4	5	2	6	5
52	Marine/Pleasure & Light Commercial	1	2	5	7	1	5	5	2	6	7	8	3
53	Commercial	1	2	7	7	1	5	8	1	4	6	8	5
54	Mobile Refrigeration	3	2	7	5	5	8	8	4	5	7	7	3
55	Offshore Oil Platforms	10	2	9	7	2	5	8	1	2	4	8	5
56	Passenger Cars	1	8	7	5	0	5	4	3	5	8	8	5
57	Railroad/Locomotive	3	5	7	3	2	8	9	1	7	5	5	2
58	Trucks & Busses	2	8	7	6	0	6	7	3	4	5	5	4
59	Welders	1	2	4	7	0	5	5	5	5	5	5	8
60	Lawn & Garden	0	2	2	5	0	2	2	4	8	7	7	3
61	Forestry	5	5	7	7	0	5	5	1	7	5	7	8
62	Pumps/General Purpose	2	2	2	5	0	2	2	4	8	7	5	2
63	Contractor	2	2	7	7	0	5	6	4	7	4	6	3
64	Fire	0	1	2	2	0	1	1	8	8	2	5	3
65	Rail Maint. Equip.	3	5	7	1	0	5	6	2	3	2	5	4
66	Mining/Underground	2	9	7	7	0	7	6	3	5	6	8	8
67	Surface	2	2	7	7	0	7	6	3	5	6	5	5
68	Generators/Recreational Use	0	2	5	7	0	2	3	8	8	6	7	5

10 = Very Important
5 = Average Importance
0 = Not Important

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TABLE E-1 (CONTINUED)

RELATIVE IMPORTANCE OF SELECTED ENGINE
CHARACTERISTICS OF GAS TURBINE APPLICATIONS

	Applications	Ability to Switch Fuels	Emissions	Efficiency	Noise & Vibration	Heat Recovery	Extended Maintenance Interval	Long Life	Startability	Engine Cost	Engine Weight	Engine Physical Size	Load Following
69	Power Generation												
70	Emergency	3	2	2	2	0	3	2	9	7	2	5	8
71	Standby/Peaking	3	5	7	5	2	5	5	3	6	2	5	8
72	Remote	3	2	8	2	0	9	8	6	4	2	3	8
73	Mobile	6	2	6	5	0	5	5	2	7	8	8	8
74	Pumping												
75	Pipelines/Transmission	0	2	7	2	8	8	8	2	5	2	5	2
76	Marine/Propulsion	3	2	8	7	5	7	7	2	6	6	7	2
77	Gas Compression/L faction	3	7	7	6	5	7	7	4	5	2	5	2
78	Automotive	1	7	8	6	3	6	5	3	7	8	8	5
79	Military/Tanks	7	2	7	8	0	7	4	8	2	7	8	5
80	Generators	7	2	7	8	0	5	4	8	2	7	8	8
81	Industrial Drives	1	7	7	6	5	7	7	4	5	2	5	5

10 = Very Important
5 = Average Importance
0 = Not Important

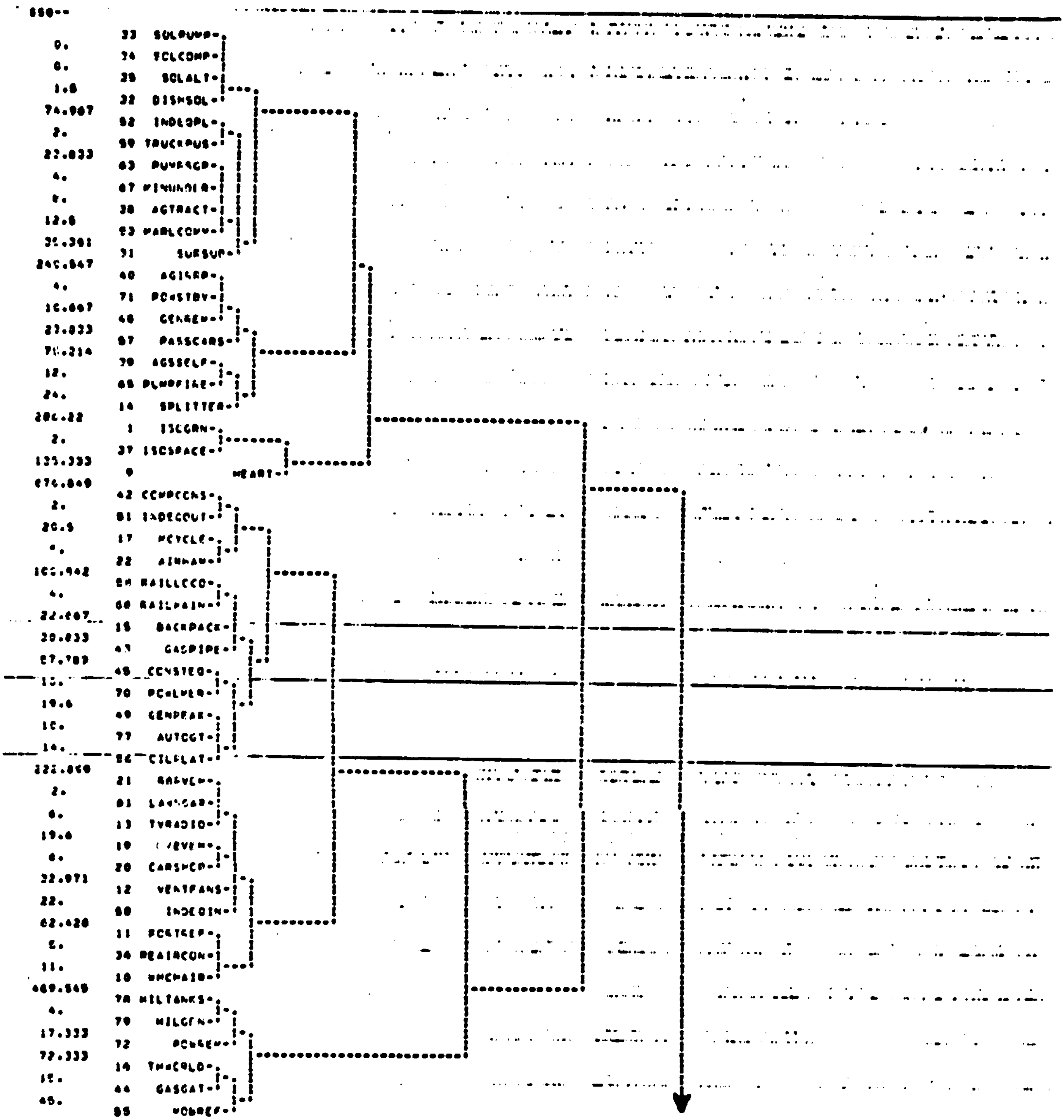

FIGURE D-1

RESULTS OF CLUSTER ANALYSIS

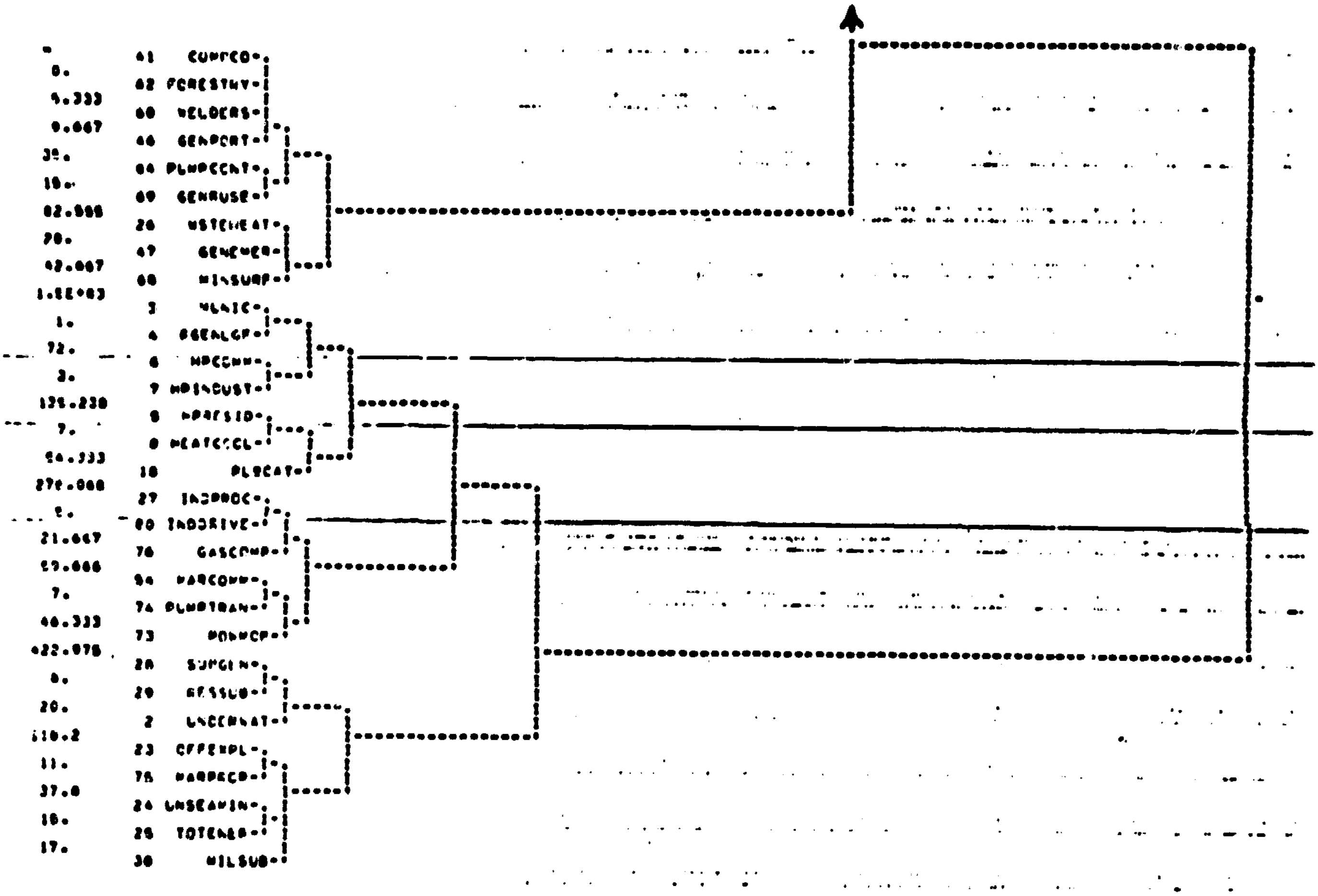

FIGURE D-1 (Continued)

APPENDIX E

SELECTED FOREIGN APPLICATIONS OF STIRLING ENGINE TECHNOLOGY

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APPENDIX E

SELECTED FOREIGN APPLICATIONS OF STIRLING ENGINE TECHNOLOGY

1.0 BACKGROUND

The Stirling engine applications study of this report focussed on domestic applications of Stirling engines. Clearly, if Stirling engines are successfully developed they would eventually be used on a worldwide basis. This larger potential world market could provide a major incentive for industry to develop specific Stirling engine systems. There are reasons to believe that some applications of Stirling engines may become commercialized abroad before they are accepted in the U.S. for a variety of economic and needs oriented reasons. This could result in foreign manufacturers applying the results of the large U.S. Stirling engine technology program to Stirling engine applications for foreign markets and possibly even eventually exporting systems to the U.S. as the market develops.

In this appendix two examples of potential foreign applications are briefly discussed.

(a) Gas Fired Heat Pumps and Total Energy in Japan

(b) Biomass Fired Rural Power Systems

Japan is giving considerable emphasis to developing gas fired heat pumps and total energy systems in order to even out large seasonal variations in electrical and gas loads. The government is providing significant incentives to accelerate the commercialization of residential and commercial size systems and Stirling engines are being given special emphasis for the lower capacity systems.

There is an increasing need for providing small amounts of power in rural areas of developing countries for such critical functions as irrigation pumping, cold storage, and village lighting. Simple biomass fired Stirling engines (possibly using hot air engine configurations) could serve this need as an alternative to Diesel generators in those heavily wooded countries having ample biomass resources.

2.0 GAS FIRED HEAT PUMPS AND TOTAL ENERGY SYSTEMS

2.1 Background

There is a great deal of interest in Japan in expanding the use of gas fired air conditioners, heat pumps, and total energy systems. Most commercial practice to date is with absorption air conditioning systems. The market for absorption units (primarily commercial sizes of 20-100 Tons) is about 5,800 units per year.

Policies and strategies of the Japanese government and the Ministry of International Trade and Industry (MITI) concerning gasified air conditioning and total energy were set in 1980. They called for one third of total air conditioning energy needs to be supplied by gas by 1990. The reasons for this policy were:

(a) To even out the consumption of both gas and electricity on a seasonal basis and, thereby, more effectively use production and transmission facilities.

(b) To save on oil imports and increase the use of LNG for which favorable long-term import contracts were being established.

At the beginning of 1981, the government announced definite plans to promote the use of gas driven air conditioning systems. Two primary goals of these plans were to (i) reduce the equipment cost difference between electrically and gas driven systems and (ii) to develop a small size engine driven heat pump system for residential and light commercial applications.

2.2 Government Policies

Consistent with the above general goals, the government, in cooperation with industry, set out to both encourage highly focussed R&D activities and to establish policies which would encourage the use of gas fired heat pump and total energy systems. Specific resources either implemented or under active consideration are discussed below.

A. Medium and Large Size Commercial Equipment (more than 50 tons of cooling capacity)

A.1 Reduction of Equipment Cost

- Foundation of low interest funds through Japan Development Bank

  Gas fired air conditioner was picked up as one of the subjects of application of low interest loan for the promotion of alternative energy use.

- Foundation of low interest funds through the municipal treasury for minor enterprises.

- Tax deduction or special depreciation system

  Under the taxation system for promotion of investment within energy management policy, the special tax deduction or special depreciation system can be applied for new investments

- Deduction of fixed property tax

  The gas fired air conditioning equipments having certain specifications can be an applicable equipment of the deduction system of the municipal fixed property tax for energy saving equipment

A.2 Reduction of Running Cost

- Exemption of Gas Tax

  Gas tax (2 percent of total consumption) will be exempted if the gas is supplied under the contract for air conditioning use in summer

- o **Discount Gas Rate**

  Gas rate will be discounted under the contract for air conditioning use in summer called load adjustment contract.

B. Small Size Commercial and Home Use Equipment

So far the small size gas fired absorption type cool/hot water suppliers have less cost competitiveness than electric motor driven heat pumps. Then, MITI supported and subsidized the establishment of the "Research Association for Gas Engine Heat Pump System." As for the detail of this research association refer to 2.3.

C. Other Initiatives

C.1 Seasonal Electricity Rate

The electricity rate for commercial use in July, August, and September is 10 percent higher than other months to reduce the air conditioning electricity needs in the summer.

C.2 Use in Government Facilities

The Ministry of Construction changed the specification of machinery facilities for governmental use and added gas fired air conditioning system as standard.

2.3 Gas Utility Strategies and Programs

A. General

There are 248 gas utilities in Japan with only three having a dominant position. All three utilities (Tokyo Gas, Osaka Gas, and Tomo Gas Companies) are quite enthusiastic to spread the use of gas engine driven heat pumps and total energy systems.

B. Definite Plans

The major gas utilities are pursuing their interest in gas driven heat pumps/total energy systems through a number of initiatives with the government and industry. These are discussed briefly below.

B.1 Own Activities

- The utilities changed their organizations and established new sections for development and use of gas engine driven heat pumps and total energy systems.

- The utilities are actively installing and testing gas engine driven heat pumps for their own use developed by collaboration with equipment manufacturers.

- The utilities are publishing technical papers and brochures for the advertisement of gas engine driven heat pumps and total energy systems.

B.2 Activity Through the Japan Refrigeration and Air Conditioning Industry Association

- The utilities organized a study tour to West Germany for gas engine driven heat pumps and total energy systems and published the report.

- The utilities tied up with equipment manufacturers and published guide book of gas fired absorption type cool/warm water supplier.

B.3 Activity Through the Research Association for Gas Engine Heat Pump System

- The general R&D goals of this organization were established as:
  1981: Basic design prototype system test with 900 million yen ($3.5 million)

1982: Advanced model and field test model tests with 1 billion yen ($ 3.8 million)

1983: Field Test with 800 million yen ($3.1 million)

o Targets of the development program

COP for home use (1-2 USRT class)
  Cooling 0.85
  Heating, Hot Water 1.37

COP for small size commercial use (8-190 USRT class)
  Cooling 0.90
  Heating , Hot Water 1.57

Span of Life: 10 years

Maintenance: 1 time per year

Exhaust Gas: Equivalent to boiler exhaust

Noise Level
  Home Use: Less than 50 DB
  Commercial Use: less than 60 DB

o Major R/D Items of the Development Program

Matching of engine and compressor

Development of multi-vane rotary, rolling piston and screw compressor

Development of dedicated engines

Deve.ᐩpment of the system fully utilizing wasted heat of engine

- Members of the Association

  3 major gas utilities

  6 engine manufacturers

  7 compressor manufacturers

2.4 Status of Engine Driven Heat Pump and Total Energy Systems

Both I.C. engine and Stirling engine driven heat pump and total energy system developments are being pursued in Japan. There appears to be good agreement that while I.C. engine driven systems might be applicable for larger capacities (50 Ton+) their use in smaller sizes is still open to question. Therefore, most efforts for Stirling engine developments are focussed in smaller capacity units (3-30 kW). The status of both I.C. engine driven and Stirling engine driven system is discussed briefly below.

A. Gas Engine (I.C.) Driven Systems

About 15 internal combustion engine driven heat pumps with capacities ranging from 20 to 170 tons have been installed over the last few years (Table 2.1).

All systems are for cooling/heating use as in electric motor driven heat pumps except the last one which is for heating use only. System prices are not available but are still quite expensive since a significant commercial practice is not yet established.

Currently Komatsu, Kinmon, Nippon Kokan, Sanyo Electric, Shinko Zoki, Kobe Steel, Maekawa Seisakusho are trying to promote the sales of gas engine driven heat pumps and total energy systems.

Sales of commercial size systems are expected to increase partly as a result of favorable policies. It is hoped that the small size home use system will be marketed from 1984 or 1985 after the research (at Research Association for gas engine heat pump system has been successfully completed.

Table 2.1

INSTALLATION OF ENGINE DRIVEN HEAT PUMPS IN JAPAN

YEAR	NUMBER CAPACITY (Tons)	MANUFACTURER
1980	1-30 USRT	Kinmon Seisakusho
1981	1-170	Nippon Kokan
	1-18	
	1-41	Komatsu
	1-20	
	1-33	Niigata Tekko
	1-160	Komatsu
	2-110	
1982	1-70	Komatsu
	1-20	
	1-70	Komatsu
	1-41	Kinmon Seisakusho
	1-169 MCAL/H	Kinmon Seisakusho

B. Stirling Engine Development Programs

The government, private industry, and universities are working collaboratively to develop Stirling engine systems - primarily for heat pump and total energy systems for residential and light commercial applications.

B.1 Governmental

Under the MITI's Moon Light project, industrial technology board set the R&D program with the budget of 10 Bil Yen ($40 million) for 6 years beginning from 1982.

The program consists of two parts. One is to undertake studies at the national laboratories, and another is at private companies' laboratories under the control of New Energy Development Organization (NEDO, established in 1980, Special Public Corporation.

- o Target of Development

  A-1 for air conditioning use
  - Capacity: 3 kW, 30 kW
  - Efficiency
  - Fuel: Natural Gas
  - COP, Cooling: 1.43, 1.57 incl. hot water supply
  - COP, Heating: 1.49, 1.63
  - Exhaust Gas: Equivalent to boiler exhaust
  - Span of Life: 10 years
  - Maintenance: 1 time per year
  - Noise Level: 45 DB, 60 DB

  A-2 for other use
  - Capacity: 30 kW
  - Efficiency: 0.37

  Other spec is the same as air conditioning use engines
- o Study items are:
  - Components design, development

- System design, development
- Development of small size air conditioning plant using heat pump and Stirling engine
- Assessment and evaluation of the proper system
- Use of variety of fuels

o Program Schedule is:
  - At the end of 1984, intermediate evaluation of the study will be done, and the proper Stirling engine will be selected.
  - By the middle of 1987, the practical Stirling engines will be developed and completely tested.

B.2 Private Sector

Several private companies are both supporting the MITI sponsored effort in Stirling engine development and doing their own R&D. The major corporate efforts in the Stirling engine field are:

Aisin Seiki:
Developing Automotive use and industrial use engines. Has a collaboration program with Tokyo Gas Company.

Mitsubishi Electric:
Developing air conditioning heat pump use Stirling engine. Currently has the one with 1.5 kW output using the gas at 1.5 MPASCAL between 650°C and 50°C.

Kawasaki Heavy Industries:
Aiming at the air conditioning applications and has a cross licensing agreement with Sunpower Corporation of the United States.

In addition to the above, all the automotive manufacturers have had at one time or another a Stirling engine program. These programs have usually involved assessing the potential for Stirling engines in automotive applications and have not resulted in significant hardware oriented programs.

B.3 Universities:

Several Universities are also working with MITI and the gas companies in the Stirling engine field. Two such activities are:

A. Meiji University: Developing a 6 kW Stirling engine for solar power applications.

B. University of Tokyo: Supporting Tokyo Gas and developing a Stirling engine with 7.02 kW/120 rpm output for commercial heat pump applications.

2.5 Conclusions

The Japanese are actively pursuing the development of Stirling engines for heat pump and total energy applications. In this effort they are closely reviewing the experience in Stirling engine technology in the United States and Europe and adapting this experience to their own needs in, at least, one case via license agreements with a U.S. company.

Government policies relative to gas pricing, R&D funding, and taxes have been developed to accelerate the introduction of gas fired systems (Stirling engines and others) so that, by 1990, they would displace 30 percent of the electricity now used in air conditioning functions. This could result in a market for over 50,000 units per year in residential and commercial applications with a capacity of about 500 MW (assuming average system size is 10 kW; i.e., sales weighted toward light commercial, institutional, and central multifamily units). Pursuing this policy could provide Japanese industry with a strong position in Stirling engine technology so that by the mid to late 1980's, efforts to use natural gas in similar manner in the U.S. might well be based on Japanese technology.

3.0 BIOMASS FIRED RURAL POWER SYSTEMS

1.0 Introduction

There has been increasing interest over the last few years in alternative approaches for providing small amounts of power to rural populations in developing countries. The critical needs for power in such areas include irrigation pumping, refrigeration of produce, and minimal villages ar home lighting. In many cases the amounts of power needed are quite small so that the provision of 1-10 kW of power for a few hours a day would suffice.

In the past such minimal power needs were often satisfied by operation of small Diesel generators or extension of the grid, (if they were satisfied at all). More recently there has been increasing interest in using photovoltaics to satisfy these distributed low power needs. Photovoltaics are technically very well suited for such applications due to their lack of moving parts with resultant potential for long, almost maintenance free, operation.

The costs of photovoltaic power units are, however, quite high with system costs now being about $20,000-$30,000 per peak kW. These costs are, however, projected to decrease greatly by the mid 1980's to $3,000 to $6,000 per peak kW. At these lower costs, photovoltaics could be a very attractive option for supplying critical power needs in rural areas of sunbelt countries.

An alternative system for using indigenous resources to provide small amounts of power in rural areas would be a biomass (wood, charcoal, rice husks, etc.) fired Stirling engine. Such a system would have the advantage of being able to provide power on demand even during periods of cloudy weather or at night. As indicated in the following discussion, a reliable biomass fired Stirling engine might be a lower cost option than photovoltaics in those countries with large biomass resources. Such countries include those in the rain belt areas of the tropics in Africa, Latin America, and parts of Asia. There could be a large market, therefore, for such an engine in the 1-10 kW output range if:

- Its operation were simple enough for use by rural populations.
- Its design was consistent with maintenance and repair in the field.

- It could operate with a wide range of locally available biomass fuels.

Several Stirling engine systems under development, particularly those low power density systems using air as the working fluid could meet these requirements.

3.2 Potential Economics of Biomass Fired Stirling Engines

The Stirling engine, diesel engine, and photovoltaic options for rural power generation differ greatly in initial cost, fuel form, fuel cost, system life, and operations and maintenance costs. A summary of these characteristics for each system is given in Table 3.1. The Stirling engine costs shown are preliminary estimates based on discussions with firms developing such engine and comparison of Stirling engine configurations with I.C. engines in a similar power range. The photovoltaic systems costs are industry projections for the 1986 time period when a commercial biomass fired Stirling engine might become available. The size range of systems being considered for rural applications is up to 50 kW. It is assumed for economic calculations that, on the average, the engine generation systems will provide about 3000 kWh per installed kW annually (8-10 hours per day operation), and the photovoltaic systems will provide about 1600 kWh per peak kW annually corresponding to daily operation in a sunny location. In order to judge the competitive position of Stirling engines relative to diesels and photovoltaics, an economic analysis comparing them is presented here. The economic index utilized is the levelized cost of energy (LCOE).[18]

The levelized cost of energy evens out the varying costs associated with the system over its lifetime into an equivalent, uniform cost stream before calculating the cost of energy from the system (in $/kWh).

This process has the advantage of being able to compare systems with widely differing initial costs, fuel costs, and maintenance schedules on an equal footing. The LCOE is the sum of the present values of the original set of periodic costs, multiplied by the required capital recovery factor, then divided by the annual energy output. Here, a discount rate of 15 percent is

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Table 3.1

CHARACTERISTICS OF PHOTOVOLTAIC, STIRLING ENGINE, AND DIESEL ENGINE SYSTEMS

	STIRLING ENGINE	DIESEL ENGINE	PHOTOVOLTAICS (1986+) $5/Wp Cells	PHOTOVOLTAICS (1986+) $3/Wp Cells
Initial System Cost				
5-10 kW	$1800/kW[1]	$800/kW[2]	$7200/kWp[3]	$4500/kWp[3]
40-50 kW	$ 800/kW[1]	$300/kW[2]	$7200/kWp	$4500/kWp[3]
Annual Operation and Maintenance Costs				
	5% Initial Cost	10% Initial Cost Overhaul Every 5000 hrs of Operation @ 30% Initial Cost	2% Initial Cost	
Fuel Form	Biomass[4]	Diesel Fuel	Solar Energy	
Fuel Efficiency	10-15%	20-25%	-[5]	
Fuel Cost	Free or Low Cost	Varies by Location		
System Life	10 years	10 years	20 years	

1. ADL estimates, includes engine cost plus biomass combuster controls and installation.
2. Includes engine cost plus controls and installation.
3. Includes solar cell array, power conditioning and controls, buffer battery storage, plus installation.
4. Stirling engine can utilize a number of fuel forms, however, biomass is assumed to be the principal fuel here.
5. It is assumed for this study that the PV system operates in a reasonably good insolation area, providing 1600 kWh/kWp, annually.

used to calculate the present values, and inflation is assumed to average 8 percent during the time period considered. Fuel rates are assumed to increase at the inflation rate. The results of the LCOE calculation for large and small diesel and Stirling engines, and for an equivalent photovoltaic system (using the data given in Table 3.1) are shown in Figure 3.1. These curves all assume that the local biomass fuel is obtained at no cost. Using this assumption, as diesel fuel prices increase about $1.25 per gallon, even the small Stirling engine is competitive with the diesel engine. Biomass powered Stirling engines at $1800/kW installed are much cheaper to purchase and operate than equivalent photovoltaic systems installed at $4500/kWp, on a levelized cost of energy basis if the biomass fuel for the Stirling engine can be obtained at zero cost.

Based on the economic analysis of system options, it is apparent that the Stirling engine, even at $800-1800/kW, is in a good competitive position for foreign power markets where small diesel engines and photovoltaics are now being considered.

3.3 Overview of Foreign Market Potential

A list of some of the potential applications for biomass fired Stirling engines is given in Table 3.2. These applications are presently being addressed by photovoltaic systems and/or diesel engines. In this section the present and projected sales of diesel engines and photovoltaic power units into these market segments is reviewed. These estimates provide a practical upper limit to the potential for biomass fired Stirling engines. The Stirling engine market was then estimated by assuming a modest percentage of the diesel/photovoltaic market would be served by Stirling engines if an engine with the required characteristics were made available. The intention of this exercise is primarily to provide a highly preliminary sense of potential market size and to indicate that these markets are of sufficient magnitude to be of commercial interest.

A. The Photovoltaic Market Potential

The NASA/Lewis Research Center (LeRC) has been supporting both DOE and USAID in

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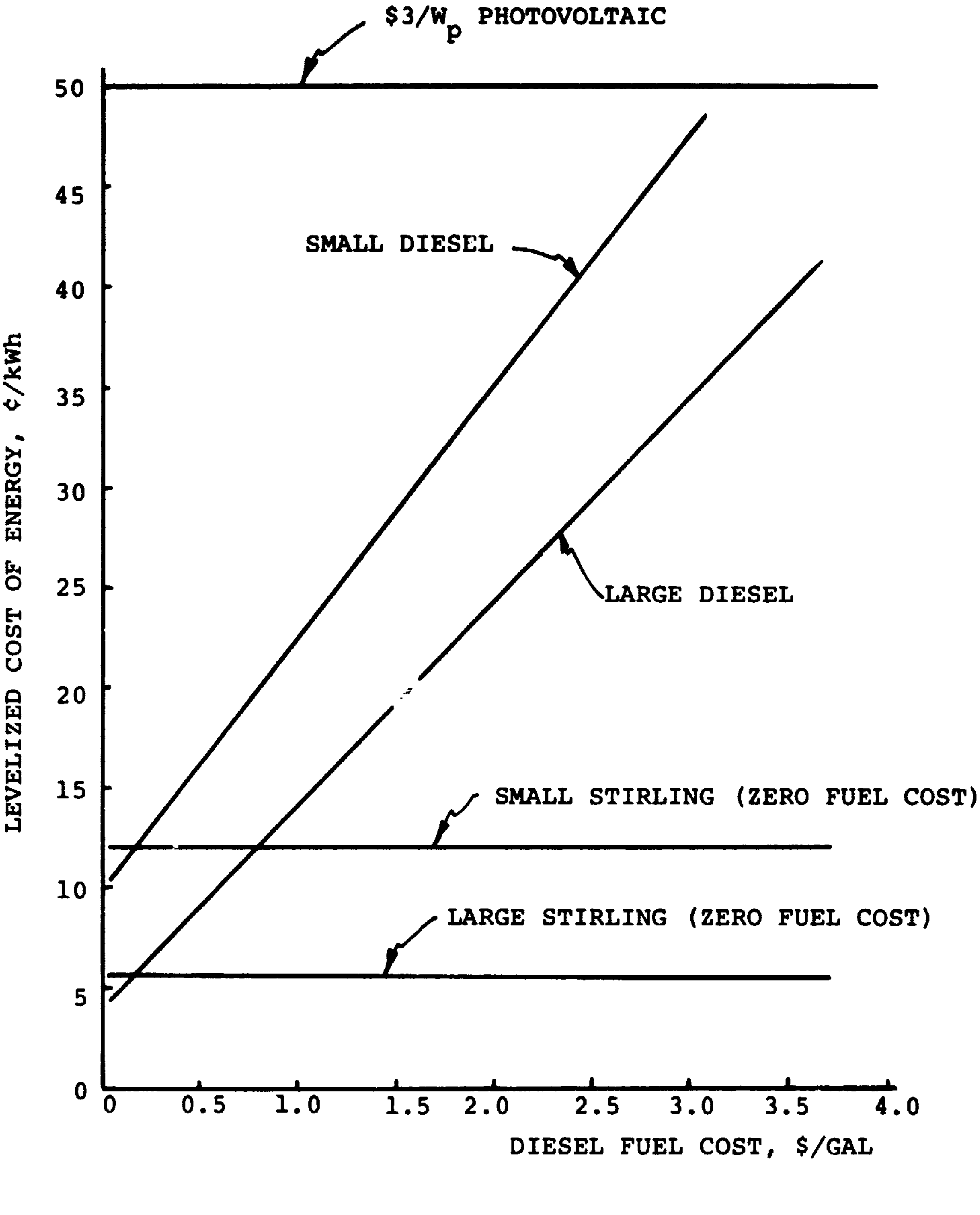

Figure 3.1 LEVELIZED COST OF ENERGY AS A FUNCTION OF FUEL COST (3000 hr operation annually)

Table 3.2

DEVELOPING COUNTRY APPLICATIONS OF RURAL POWER SYSTEMS

Irrigation and Potable Water Pumping

Prime and Standby General Village Power

Agriculture, Small Industry, Construction and Mining

Communications

Consumer Products

Corrosion Protection and Marking and Warning Devices

SOURCE: Arthur D. Little, Inc. and References 7, 11, and 14.

developing photovoltaic power units for use in both domestic and international applications and overseeing the installation of field demonstrations.[1,2,3] LeRC has and continues to undertake country specific market studies for photovoltaic systems in order to ensure proper selection of systems for development.

Early work by LeRC analyzed the energy needs of developing countries and focused on these countries that do not have the ability to meet those needs using domestic fossil fuel, nuclear or hydro power. The technical suitability of solar energy for these countries was then examined in order to estimate their solar market potential.[3] Specific applications, such as water pumping, were also examined in detail.[4] This study concluded that the near-term domestic market for photovoltaic systems for waste water treatment and drainage, potable water, and crop irrigation alone, using the estimate of 100 million small (1/3 to 1/2 hp) pumping systems required for irrigation in the LDCs, was 6000 MW_p.* In addition to point out the importance of the LDC market to the total world market for photovoltaic water pumping systems, Rosenblum, et al, observed that the World Bank directly or with client countries financed in the LDCs $3,595 million of agricultural projects in 1976. The World Bank alone financed $743 million of irrigation projects and $347 million of water resources and sewage projects in the same year.

LeRC has more recently undertaken detailed market studies for cottage industries[5] and village power.[6] The market assessment study for cottage industries[5] concluded that, although the existing near-term photovoltaic (PV) market is estimated to be 70,000 MW, this potential will probably not as a practical matter be approached within the next decade. The study defining the market for PV village power[6] concludes that up to 1,000 MW_p of the total village potential (20,000 MW_p) can be penetrated over the next 10 years (1980-1990). Barriers to market penetration mentioned include unfamiliarity with PV systems, preference for grid extension, and the need for PV to be experienced as a demonstrated technology. The lower end of the 1990 range is

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* MW_p - Peak megawatts of photovoltaic capacity. A "peak" megawatt is capacity measured under bright midday solar conditions.

consistent with the Pacific Northwest Laboratory Export Potential for Photovoltaic Power Systems[7] (PNL) study figures for the village power market potential. The PNL study additionally includes market potential figures for other applications as well.

Of the recent major photovoltaic foreign market studies[7,8,9,10] the most detailed is the PNL report.[7] The results of all the PV market studies mentioned are reasonably consistent in their identification of major market areas, consequently the PNL study is discussed here.

The PNL report examines the market for PV technology for those applications of current interest (communications, corrosion protection, marking and warning devices, and consumer products) and applications that are expected to develop or whose economics may improve (water pumping and general village power sources). The study is based on (1) data gathered by personal and telephone interviews in the United States with PV manufacturers, distributors, and system houses as well as with current customers of PV systems such as telecommunication companies, oil and gas companies, pipeline companies, and navigational aid manufacturers, (2) potential customers including international development agencies and (3) DOE representatives who participated in ISCWG field visits abroad. Table 3.3 summarizes some of the key results of this study.

Although current applications are dominated by communications alone,[11] the market projections of Table 3.3 demonstrate that water pumping is anticipated to grow very quickly and to exceed communications by almost a factor of 2 by 1982. By 1986, current applications are projected to total 14.2 MW_p, while water pumping and village power are given as 39.0 MW_p, almost a factor of 3 increase. At \$4/MW_p installed,[8] this is a market of over \$200 million in 1986. By 1990, most of the foreign PV market is associated with water pumping and village power (103 MW_p out of a total of 129 MW_p).

Compared with PV, Stirling engines occupy a good competitive position according to the economic criteria discussed previously (Section 3.2). Thus, where the

Table 3.3

FOREIGN PV MODULE MARKET PROJECTIONS

(in Peak MW)

	1986			1990		
	L	M	H	L	M	H
1. Water Pumping	3.7	29.0	88.1	9.0	78.0	250.0
2. General Village Power Source	0.9	10.0	24.0	3.0	25.0	100.0
3. Communications	5.2	7.5	9.5	8.0	11.0	15.0
4. Corrosion Protection	3.2	4.5	4.9	6.0	8.5	11.0
5. Marking and Warning Devices	0.5	1.2	2.2	1.6	2.8	4.5
6. Consumer Products	0.7	1.0	1.3	2.4	3.5	4.4
TOTAL	14.2	53.0	129.9	30.0	129.0	384.9

(Reference 7)

Stirling engine is applicable, the limiting factors to market penetration will be biomass availability, commercial readiness, and the relative level of acceptance of Stirling engines. With this in mind, a penetration level of 15 percent of the PV market potential was assumed, with an average Stirling engine size of 5 kW, and an average cost of $1000/kW. The results of the Stirling engine share of the PV potential market are shown in Table 3.4. As indicated, this segment of the market may $11 million annually by 1990.

B. The Diesel Engine Market Potential

There is presently a large worldwide market for small diesel engines and generator sets, which are used in the range of applications indicated in Table 3.2. Although a significant amount of diesel engine market research has been carried out by Diesel Progress North American, in cooperation with Power Systems Research, Inc.,[12,13,14] a good deal of the small diesel market import information for developing countries is not readily available. However, reasonable estimates of the developing country market potential can be made based on available information from Diesel Progress and the United States Department of Commerce.[15]

An estimate for the 1980 free world production of diesel engines of all types is about eight million engines, with the United States producing about 900,000 of these. The United States exported roughly 15 percent of its diesel engines in 1980.[14] These U.S. figures can be used as a rough indicator of worldwide figures. Assuming a similar rate of export for diesel engines worldwide, about 1,200,000 diesels were exported in 1980, and perhaps 600,000 of these were in the size range under consideration. The United States sends about 30 percent of its total small diesel engine exports to developing countries, with the remainder going to industrialized countries.[15] Assuming this percentage is similar for world exports as a whole, about 180,000 small diesels were exported to developing nations in 1980.

United States diesel engine production, even with the current hiatus in the domestic diesel market, will grow in the near-term, and is expected to double over 1980 levels to about 1.8 million engines by 1990, with about 200,000 small engines in 1985, and 360,000 small engines in 1990 being exported to developing countries out of these totals. These assumptions lead to a developing country export market for small diesels of 4,000 MW in 1985 and 7,200 MW in 1990, with an average engine size of 20 kW.[14]

Employing these rough calculations to give "ball park" market figures, it is evident that there is quite sizeable diesel engine market potential in the developing countries in the near-term. Compared with diesel engines Stirling engines can be competitive especially in areas with sufficient biomass and high petroleum product prices. It is reasonable to assume that, where these conditions exist, it is possible for Stirling engines to displace about 10 percent of this diesel market potential. With an average Stirling engine size of 5 kW, and an average cost of $1000/kW, the Stirling market may be worth $180 million by 1990, and have a capacity of 180 MW. This diesel market information is summarized in Table 3.4.

C. Market Overview Summary

The value of the potential foreign market for Stirling engines may total nearly $200 million (200 MW) by 1990 assuming biomass fired Stirling engines successfully competed in 10-15 percent of the applications now or projected to be served by Diesel engines and photovoltaics.

As indicated by Table 3.4, the future potential of biomass fired Stirling engine is strongly dependent on the ability to compete with Diesel pumps and generator sets in developing country markets. The reason for this is that the annual capacity of small diesel engines is projected to be a factor of 50 larger than for photovoltaic power units even in 1990 based on the photovoltaic market estimates cited. This points out the large growth potential for both photovoltaic power systems and biomass fired Stirling engines in serving the diverse rural power needs in developing countries.

Table 3.4

ESTIMATE OF POTENTIAL WORLDWIDE MARKET FOR SMALL STIRLING ENGINES FOR 1985 and 1990

	1986	1990
PHOTOVOLTAICS		
Photovoltaic Market Potential, MW_p [1]	42	129
% Applicable to Stirling[2]	15%	15%
Potential Stirling Capacity, MW[3]	3	11
Estimated No. of Stirling Engines[4]	600	2,200
Value of Stirling Market ($000)[5]	3,000	11,000
DIESEL ENGINES AND GENSETS (50kW or 65hp)		
No. of Diesel Engines[6]	200,000	360,000
Estimated Capacity, MW[7]	4,000	7,200
% Applicable to Stirling[2]	10%	10%
Potential No. of Stirling Engines	20,000	36,000
Estimated Stirling Capacity, MW[4]	100	180
Value of Stirling Market ($000)[5]	100,000	180,000
TOTAL POTENTIAL VALUE OF STIRLING MARKET ($000)	103,000	191,000

NOTES:

1. Source: PNL, "Export Potential for PV Systems," 4/79, p. 2.6, medium scenario, interpolated for 1985.
2. ADL estimate, based on economic analysis.
3. Assumes 8-10 hr/day, 350 day/yr Stirling generation and 1600 kWh/kWp annual PV system output.
4. Assumes average Stirling engine size of 5 kW.
5. Assumes average Stirling engine cost of $1,000/kW.
6. Based on information on U.S. and World diesel markets from Diesel Progress and Power Systems Research, Inc. (See text).
7. Assumes an average of 20 kW per engine/genset, a reasonable average size based on engine data from Diesel Progress.

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