DOE/NASA/1005-9
NASA TM-87305

NASA-TM-87305
19860016789

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Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Division of Building and Community Systems

Prepared for
21st Intersociety Energy Conversion Engineering Conference
cosponsored by ACS, SAE, ANS, ASME, IEEE, AIAA, and AIChE
San Diego, California, August 25-29, 1986

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Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
NTIS price codes[1]
Printed copy: A02
Microfiche copy: A01

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[1] Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issues of the following publications, which are generally available in most libraries: *Energy Research Abstracts (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication, NTIS-PR-360 available from NTIS at the above address.

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Washington, D.C. 20545
Under Interagency Agreement DE-AI05-820R1005

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N86-26261 #

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ABSTRACT

An overview of the National Aeronautics and Space Administration (NASA) Lewis Research Center SP-100 free-piston Stirling engine activities is presented. These activities include a free-piston Stirling space-power technology feasibility demonstration project as part of the SP-100 program being conducted in support of the Department of Defense (DOD), Department of Energy (DOE), and NASA. The space-power Stirling advanced technology effort, under SP-100, addresses the status of the 25 kWe Space Power Demonstrator Engine (SPDE) including test results. Future space-power projections are presented along with a description of a study that will investigate the feasibility of scaling a single-cylinder free-piston Stirling space-power module to the 150 kW power range. Design parameters and conceptual design features will be presented for a 25 kWe, single-cylinder free-piston Stirling space-power converter. A description of a hydrodynamic gas bearing concept will be presented whereby the displacer of a 1 kWe free-piston Stirling engine is modified to demonstrate the bearing concept. And finally the goals of a conceptual design for a 25 kWe Solar Advanced Stirling Conversion System capable of delivering electric power to an electric utility grid will be discussed. The solar work is under an interagency agreement between DOE/Sandia National Laboratory and NASA Lewis.

INTRODUCTION

FREE-PISTON STIRLING technology was started with the work of William Beale at Ohio University around 1962. This early work resulted in small-scale fractional-horsepower engines which demonstrated basic engine operating principles. The potential advantages (hermetically sealed, high efficiency, and simplicity) of this type of engine became more widely recognized in the early 1970's. This recognition resulted in larger companies taking an interest in its development for heat pumps and solar applications.

Shortly thereafter, the Department of Energy (DOE) took an interest in heat pump development. One area of specific interest to the DOE is the free-piston Stirling engine-driven heat pump. Coincidentally, NASA Lewis was conducting research on free-piston Stirling engines as one of several candidates for potential space-power systems. Although both applications, residential heat pumps and space power, appear quite different, their requirements complement each other. These requirements include high efficiency, the potential for long life and high reliability, low vibration, and hermetic sealing. These common requirements became the basis for a cooperative interagency agreement (IAA) between DOE/Oak Ridge National Laboratory (ORNL) and NASA Lewis signed September 1982. The research resulting from this IAA covers generic free-piston Stirling technology applicable to both space power and terrestrial heat pump application. This generic technology effort will not be be addressed further as part of this paper due to a length restriction. However, this work is very important to better understand the fundamentals of free-piston Stirling technology. A brief review of this work is presented in Ref. 1.

In 1983 the SP-100 program was established through a memorandum of agreement between the Department of Defense (DOD), NASA and the Department of Energy to jointly develop the technology necessary for space nuclear-reactor power systems for military and civil applications. One major element under the SP-100 project organization is the Aerospace Technology element. The critical technologies to be developed under this element include static and dynamic energy conversion subsystems. One such subsystem is the Stirling engine power conversion unit. The free-piston Stirling technology work conducted at or managed by NASA Lewis in support of the SP-100 program is discussed in this report.

Although this report primarily addresses free-piston Stirling engine activities under the SP-100 program, NASA, under both DOE and NASA funding, has (a) conducted studies and research in generic kinematic Stirling technology; (b) provided technical support for a DOE/Jet Propulsion Laboratory (JPL) Stirling Solar Thermal Project; and (c) managed the Automotive Stirling Engine (ASE) development project. Reference 2 provides an overview of the DOE/NASA ASE Program. References 3 to 15 list a series of reports which summarize both NASA directed and NASA conducted kinematic and free-piston Stirling work.

In addition to the SP-100 and DOE/ORNL-NASA Lewis projects, an IAA has recently been signed between DOE/Sandia National Laboratory and NASA Lewis to utilize Stirling space technology for solar thermal terrestrial application for generating solar derived electrical power.

SP-100 FREE-PISTON STIRLING BACKGROUND

The free-piston Stirling system was one of four concepts considered for the power conversion unit for the SP-100 program. After an extensive concept review, covering about an 18-month period, the thermoelectric system was chosen for the baseline 5-yr Phase II Ground Engineering System (GES) program with the Stirling concept continuing under the NASA SP-100 Advanced Technology program.

Phase I of the SP-100 program was a 3-yr Concept-Definition Phase which included development of power system conceptual designs as well as demonstrations of technical feasibility of each concept. The Phase II GES program will demonstrate the technology readiness to proceed into the Phase III Flight program. This third phase is also a 5-yr program entailing the flight systems qualification, fabrication, and assembly, and culminating in a mid-90's initial launch. NASA, in coordination with the overall SP-100 development program, initiated an SP-100 Advanced Technology Program. The objectives of the Advanced Technology program are to augment the GES engineering development and ground testing of major subsystems and to provide significant component and subsystem options for increased efficiency, survivability, and growth, at reduced weight and high reliability. Thus, enhancing the chances of success for the overall SP-100 power system development.

These goals will be obtained through the key elements of the broadly based program which include: systems analysis to guide the overall effort and advanced technology development in the areas of Energy Conversion, Thermal Management, Power Conditioning and Control, Space Power Materials and Structures, and Spacecraft Environmental Effects. Building upon the technology advancements accomplished in Phase I of the SP-100 program, the advanced Stirling technology conversion project is one important element of the program and is the basis of this report. The key Stirling technology areas needed for this broadly based program are listed in Fig. 1.

The Stirling free-piston system has many attractive attributes, several of which are tabulated in Fig. 2. Specifically, the Stirling cycle is the most efficient thermodynamic heat engine cycle that exists. Of the concepts considered for SP-100 selection, the Stirling cycle has the highest efficiency for the same given heat input and heat rejection temperatures. Because the Stirling system employs the gas bearing - either hydrodynamic or hydrostatic - there is the potential for long life and high reliability.

A system composed of a Stirling engine/linear alternator has only two moving parts per cylinder - that is the displacer and the power piston/alternator plunger. The result is a relatively simple configuration. An opposed-piston engine with reciprocating components along the same axis - such as the Space Power Demonstrator Engine which will be discussed later in this report - is an inherently balanced power module. A single-cylinder engine can be balanced either actively or passively using a spring-mass combination. A passive system is good for only a narrow frequency range; and an active system which has a variable spring rate, provides a wide range over which the vibration can be significantly reduced.

Free-piston Stirling engines contain no sliding rod seals such as those present in the kinematic concepts. The energy conserved by not having to overcome the losses in the frictional rod seals is not totally free. The free-piston Stirling concept utilizes gas springs which have hysteresis losses. At the present time, it is not known whether the free-piston concept or the kinematic concept is the most efficient, but it is felt that there should not be much difference between the efficiencies of the two concepts. The fact that there is no oil inside the engine makes the free-piston a strong candidate for long life. There is no chance of getting oil contamination into the regenerator and degrading engine performance. An opposed-piston free-piston Stirling engine with a common expansion space, theoretically has the potential for graceful degradation in the event that one engine has larger losses than the other. Both pistons then produce equal power, but at a reduced level.

The power output of the free-piston is very flexible in that not only is a linear alternator possible, but so are other concepts. These concepts include the hydraulic output with a hydraulic motor/pump and a conventional rotating alternator; and a hydraulic drive/gas compressor output which can provide gas turbine power to a conventional or high speed alternator.

FUTURE SPACE POWER PROJECTIONS

Over the next several decades, the amount of electric power required in space is expected to grow immensely. Today's larger satellites require almost 10 kWe of power. Most of these satellites are powered by solar arrays with storage batteries. Tomorrow's space platforms will continuously require hundreds of kilowatts; and some will periodically consume many megawatt-hours of energy. These space platforms will include manned space stations, communication stations, surveillance platforms, and defensive weapons. These large power systems will be quite different from today's solar arrays.

Projections of space power growth tend to show broad trends as shown in Fig. 3. These broad trends are a direct result of uncertainties in future mission capabilities and needs. It is, however, clear that future space power needs may be several orders of magnitude greater than anything that has been accomplished to date. The challenge for the space power planner is formidable - to select power technologies that can meet the projected trends and adapt to multiple users. One potential solution is the use of dynamic power conversion units - either solar or nuclear.

Figure 4 is an artist's conception of an SP-100 Stirling engine system. The concept uses a nuclear reactor and shield along with both fixed and deployed radiator panels. Thermoelectric electromagnetic pumps are employed to transport the hot liquid from the reactor to the Stirling engines.

THE SPACE POWER DEMONSTRATOR ENGINE (SPDE)

The SPDE was designed and fabricated by Mechanical Technology Inc. (MTI) of Latham, NY. The engine is currently under test at this facility. Initial successful operation of the engine occurred in less than 16 months from start of work - a significant achievement. The nominal design was 25 kWe from the two opposed-piston Stirling engine - linear alternator system. A photograph of the engine is shown in Fig. 5, and a cutaway artist's conception is shown in Fig. 6. The engine is about 1-1/4 m in length and about 1/3 m in diameter. It is suspended from the ceiling by four vertical straps. This flexible suspension was the test configuration and no discernible vibration was observed during operation. Accelerometers mounted on the engine housing indicated maximum amplitudes (peak-to-peak) of less than 0.01 mm which corresponds to a "g" of less than 0.2. A general description of the engine is given in Refs. 17 and 18.

Because of the tight schedule to design, fabricate, and test the engine within a 16-month period, the maximum engine temperature for initial testing was limited to 650 K. The cost of a liquid metal facility (necessary for higher temperature operation) was also a factor in selecting 650 K as the heater temperature. The cold or cooler temperature was maintained at 325 K in order to operate the engine at a temperature ratio of 2. The temperature ratio of 2 was chosen for a minimum weight system (including reactor and radiator).

The SPDE is a development engine and, as such, is not a final space configuration. However, with straight-forward material substitutions and replacing bolts and flanges with welds, the SPDE specific mass at design power is reduced to 7.2 kg/kWe from the laboratory specific mass of 12.7 kg/kWe as tabulated in Fig. 7.

Figure 8 compares the predicted half-design pressure electrical output power to the initial corresponding experimental data; and later to that same experimental data corrected for a power measurement error. At the half pressure condition the code predictions average about 15 percent higher than the test data. As the power level is increased, by increasing the pressure (which also increases the frequency), the discrepancy between predicted and measured power increases. The test data is about one-half that of the predicted value at the design condition. Figure 9 compares the design power (predicted versus experimental) at 150 bar from half to full piston stroke. At present, the only apparent engine drawback is the power shortfall. A concerted effort is being conducted, by both MTI and NASA, to resolve this problem. On balance, the mechanical operation of the engine has been flawless. Both power pistons (alternator plungers) and one displacer have been completely trouble-free. One displacer drive was troublesome until a positive cylinder alignment was incorporated into the design. In order to understand why there is a power shortfall additional instrumentation is being added to the engine as well as a complete recalibration of all flow meters, resistance temperature devices, and pressure sensing devices. Thermocouples will be located at the interface of each heat exchanger (i.e., heater - regenerator, regenerator-cooler, etc.). Figure 10 shows a technician feeding thermocouples through a pressure vessel penetration hole.

A series of diagnostic tests were conducted in order to isolate potential power shortfalls. The tests consisted of cold and at temperature motoring tests with the displacer (one of the two moving parts per engine) locked in place. A motor-generator set supplied power to motor the alternator of the SPDE. The purpose of these tests was to determine whether gas leakage and/or hysteresis are a cause of the power shortfall. Additional motoring tests will be conducted with both displacer and piston unlocked at a temperature ratio of 1. This test will verify whether leakage and/or hysteresis are contributing to the power shortfall. Preliminary indications are that leakage or hysteresis or a combination are not the problem.

An early prognosis, though by no means final, appears to key on an insufficient amount of heat transfer into the engine. This could result from:

- maldistribution of molten salt flow
- maldistribution of gas flow
- regenerator ineffectiveness (by-pass flow or poor design)
- oscillating flow effects and
- increased conduction losses.

The SPDE engine is at the forefront of Stirling technology and operates at 105 Hz, 1.75 times greater than previously designed Stirling engines (the equivalent to an automobile engine at 6300 rpm). As such, the higher frequency generates large dynamic oscillating forces on the regenerator which have resulted in regenerator fretting and damage. Previous free-piston Stirling regenerators - due to the low pressure ratio of free-piston engines - were not sintered or canned and maintained their integrity over long period of operation.

As an example the nominal 3 kW MTI Endurance Engine ran over 5500 hr without any regenerator problems. Nevertheless, Fig. 11 shows a comparison between the uncanned, unsintered screen regenerators before testing and after only about 20 hr of 105 Hz operation. Sintered and canned regenerators are on order for future testing.

HYDRODYNAMIC GAS BEARINGS

The SPDE engine was designed with hydrostatic gas bearings for expediency, rather than as the preferred space-power design which incorporates hydrodynamic gas bearings. Hydrodynamic bearings for free-piston Stirling engines provide the potential of simplicity in design accompanied by improved efficiency when compared to hydrostatic systems.

The following statements hold for hydrodynamic gas bearings: (a) the pressure amplitude of the piston gas spring can be reduced considerably accompanied with a corresponding reduction in hysteresis loss in the gas spring. This reduction in pressure amplitude can be made because the supply pressure for the bearing is no longer taken from the piston gas spring; (b) standard engineering practice indicates that the same degree of bearing stiffness can be achieved by a design combination of rotating speed of the piston and piston/cylinder clearance; and (c) seal losses in both systems can be about equal.

Sunpower Inc. of Athens, Ohio under contract to NASA Lewis has demonstrated a spin-lubricated hydrodynamic gas bearing concept on a displacer. This was performed on a 1 kW free-piston Stirling engine which was modified for this test. Even though the Sunpower test engine is a smaller engine than the SPDE engine, similarity laws governing the design of gas bearings are used such that the test results are directly applicable to full-scale engines. For example, even though the pressure in the SPDE engine is ten times greater than that of the test-bed engine, the bearing clearances differ by a factor of less than two. Figure 12 shows a schematic arrangement of the Sunpower demonstration whereby both the displacer and piston are retrofitted with simple impulse turbine blades designated as "T" in the figure.

Many different configurations were tested by Sunpower including both a full and partial stator located at the cooler port. The displacer spun with as few as 16 blades without a stator but only at a few hertz. With 64 to 128 blades, the displacer spun at an acceptable rate above 5 Hz. However, it was important that the displacer was accurately positioned relative to the cooler port opening at the time of maximum port flow. As a consequence a stator was placed at the cooler port. A schematic showing the stator-turbine configuration is shown in Fig. 13. Using a full stator left no unobstructed space for the return gas flow, and as a consequence resulted in high displacer damping and poor engine operation. A solution was a partial stator enabling easy passage of the gas from the compression space to the port during the half cycle in which the gas flows out of the compression space. During the flow of gas out of the stator into the compression space a spinning effect is imparted to the engine gas in the compression space, thus resulting in a more continuous torque rather than a brief impulse torque as in the configuration without a stator. Figure 14 shows some of the turbine-stator combinations that have been used during this investigation. To date the status of the displacer spin-bearing testing is summarized in Fig. 15. No instabilities have been found; however, it is very important to have accurate alignment and maintain dimensional stability. The best configuration at this time is a partial stator with a 128 turbine-blade configuration. One very important feature of the partial stator is its reduced sensitivity to displacer position and phasing. The testing at Sunpower has demonstrated successful displacer startup and sustained operation with low calculated losses at the spin range of 5 to 10 Hz. The results of the displacer hydrodynamic spin bearing investigation will be documented in a contractor report. This work will be extended under a small business innovative research (SBIR) contract funded by the DOE to spin both the displacer and piston. As part of this work the contractor will investigate any interactions between the spinning piston and displacer. Recommendations will also be made for future gas bearing work.

The Arthur D. Little Co. of Cambridge, MA has also done a considerable amount of work with hydrodynamic gas bearings on free-piston equipment. The bearing dimensions and operating conditions (e.g. frequency, rotational speed, stroke, etc.) are similar to the Stirling space power application. A.D. Little uses an electric motor principle to rotate the piston whereas Sunpower uses the impulse turbine principle. Either of these concepts hold much promise. With over 10 000 hr of noncontacting gas bearing operation on free-piston equipment, A.D. Little has certainly demonstrated concept feasibility.

25 kWe SINGLE CYLINDER CONCEPT

Under SP-100 funding, Sunpower generated parametric relationships for free-piston Stirling engine linear alternator (FPSE/LA) systems such that for specified heater-to-cooler temperature ratios, equations were established to represent the interdependency between the FPSE/LA specific mass and percent of Carnot cycle efficiency. Sunpower then used these relationships to generate a conceptual design for a 25 kWe single-cylinder space-power module (including linear alternator). The design parameters are listed in Fig. 16. The parameters above the horizontal line are specified; and those below are design optimizations. It is of interest to note that the heater material was chosen as a refractory metal alloy niobium and zirconium (Nb-1Zr). The lifetime requirement was 70 000 hr and the heater temperature was 1080 K. A cross section of the FPSE/LA design is shown in Fig. 17. Not listed under design parameters is the fact that hydrodynamic gas bearings were used on both reciprocating components, the displacer and the power piston (linear alternator plunger). The basic power module was a simple single-piston displacer design using an adaptive dynamic balance unit to minimize forces transmitted to the support structure. The dynamic balance unit, the heat exchanger assemblies, and the use of hydrodynamic gas bearings represent the only departure from conventional FPSE technology. This design incorporated approximately 180 heat exchanger assemblies, one of which is schematically shown in Fig. 18. This assembly consists of a heater, regenerator, and cooler encased in a single tubular structure. This design contrasts with the conventional multitude (1600 tube heater and 1900 tube cooler) heat exchangers used in the SPDE. It significantly reduces the number of fabrication joints and also provides a better match of heat transfer between the liquid-metal side and the helium working fluid side. Sunpower is using this single-cylinder concept, as the basis for a preliminary design. This preliminary design will have a superalloy hot end - as opposed to the Nb-1Zr hot end in the conceptual design. The average heater design temperature is 1075 K. This work is just getting underway. The preliminary design will be modified into an experimental version; and will be designed for research instrumentation, ease of component modification, and ease of assembly and disassembly. By using super alloys for the heater head it is easier, less expensive and faster to test and evaluate than a refractory metal engine. This engine, when built, will be tested at NASA Lewis in Cleveland, Ohio. In any event, heat pipes will be used to supply heat to the engine. Even though this engine will not be tested for at least a couple of years, some of the heat exchanger assemblies as previously shown in Fig. 18 will be fabricated and tested separately. Three heat exchanger assemblies will be fabricated of materials proposed for this superalloy Stirling Space Engine. The assemblies will be flow-tested under both steady state and oscillating flow to verify design parameters. The flow rig is being built by Sunpower under a small business innovative research (SBIR) contract. The award was announced recently.

The three heat exchanger assemblies will be of the same basic design but differ in internal configurations to allow flow test measurements for a range of heat exchanger dimensions. One assembly will have the dimensions as used for the design of the superalloy heat exchangers. The dimensions of the other two assemblies shall be larger and smaller, respectively.

SCALING STUDY

The free-piston Stirling engine is an emerging candidate for space-power missions using either nuclear or solar heat sources. Recent work has keyed on FPSE designs, hardware fabrication, and testing below the 25 kWe power range. However, as discussed in the section Future Space Power Projections it is readily apparent that single-cylinder engines with power outputs above 100 kWe per cylinder are very desirable. Therefore, it is important to determine whether it is feasible to design a single-cylinder FPSE/LA system in the 100 to 150 kWe range.

As a consequence, NASA Lewis is in the process of awarding a small competitive contractual effort to investigate whether single-cylinder FPSE/LA systems can be designed in the 100 to 150 kWe power range. As part of this study recommendations will also be made for configurations other than linear alternators. Are there other configurations that may offer advantages over the linear alternator configuration Figure 19 outlines the scope of the work being considered under this study. The study will cover the power range from 25 through 150 kWe per cylinder. An option to the study is to determine the maximum power per cylinder if indeed it becomes apparent that power levels greater than 150 kWe per cylinder are feasible. The study will key on engine temperature ratios in the range of 2 to 3. It is in this range that the contractor will be asked to establish parametric relationships between percent Carnot cycle efficiency and specific mass of the power conversion unit (i.e., Stirling engine plus linear alternator). This initial study will key on a temperature level of about 1050 K so that superalloys can be used. The design life shall be about 60 000 hr with helium as the working fluid and a specific mass target range of 5 to 8 kg/kWe.

SOLAR-POWERED FREE-PISTON STIRLING ENGINE FOR GENERATING TERRESTRIAL ELECTRICITY

Under the DOE's Solar Thermal Technology program, Sandia National Laboratories (SNLA) is developing heat engines for terrestrial Solar Distributed Receiver Systems. Of the available heat engine technologies, SNLA has identified the Stirling to be one of the most promising candidates to meet the DOE goals for both performance and cost.

NASA Lewis, with its background and expertise in Stirling engines, will provide the technical management for the Advanced Stirling Conversion System (ASCS). The initial work consists of a conceptual design to be awarded from a competitive procurement. The conceptual design is for a solar-to-electrical ASCS utilizing a free-piston Stirling engine. The design shall include: free-piston Stirling engine and alternator; liquid metal heat pipe receiver; and control system. The goal of this procurement is to generate the conceptual design of an ASCS capable of delivering approximately 25 kW of electric power to an electric utility grid at an engine/alternator target cost of 300 dollars per kilowatt at the manufacturing rate of 10 000 units per year. The design life of the engine/alternator is 40 000 hr. Figure 20 is an artist's conceptualization of the ASCS showing the solar receiver, heat transport system, Stirling engine, heat rejection system and encased alternator. The solar collector is not shown. Figure 21 outlines the specific objectives for the initial conceptual design. An important criterion for this conceptual study was to use technology which can be reasonably expected to be available in the late 1980's. The study will also identify key technology needs not ready by the late 1980's. It is the intent of the DOE/SNLA-NASA Lewis IAA to take full advantage of the Stirling technology evolving from both the SP-100 Stirling Space Power and the Automotive Stirling activities.

CONCLUDING REMARKS

A 25 kWe SPDE engine has been designed, fabricated, installed, and initially tested. At half design-pressure performance codes predicted 6.7 kWe under conditions at which the engine-alternator generated 6.0 kWe. This occurred at 75 bar pressure and 73 Hz. As the pressure is increased to the design pressure of 150 bar (105 Hz), the power output is about 50 percent of the code-predicted power. Early diagnostic testing points to an insufficient amount of heat transferred into the engine. Nonconventional materials such as beryllium and gold brazes have been used. With proper material substitution and replacing bolts and flanges with welds, the specific mass of the engine/alternator is reduced to 7.2 kg/kWe. This is the first free-piston Stirling designed for space application that incorporates molten salt in the heater; and is also designed for the low temperature ratio of 2. Low-power data obtained at half-design pressure show that the experimental results are about 85 percent of the predicted results. Unsintered and uncanned screen regenerators were damaged during 50 hr of 105 Hz operation. The SPDE has demonstrated that a dynamic power conversion system can, with proper design, be balanced; and the engine performed well with externally pumped hydrostatic gas bearings. Other than the power shortfall, the SPDE engine performed admirably. Testing of the SPDE will continue its steady development and will provide a test bed to evaluate new components/technologies.

The hydrodynamic spin-lubricated (impulse turbine) gas bearing concept has been successfully demonstrated on the displacer of an operating 1 kWe engine. The best configuration appeared to be a 128 turbine bucket arrangement with a partial stator located at the cooler port. No instabilities have occurred. Work will continue to extend the effort to spin both a displacer and a power piston.

A preliminary 25 kWe single-cylinder FPSE/LA and active dynamic balancing has been conceptually designed for further assessment. This design also features modular heat exchangers which dramatically reduce the number of joints and also enhance the heat transfer capability. The hot end will be limited to 1075 K and will be fabricated from super alloy material.

A scaling study will be conducted to determine the feasibility of designing a single-cylinder free-piston Stirling linear-alternator system in the 150 kW range. The initial study will key on a temperature of around 1050 K.

Another study funded by DOE/SNLA will develop a conceptual design for a 25 kWe terrestrial solar-to electrical system. The design shall include a liquid metal heat-pipe receiver, a free-piston Stirling engine, an alternator and a control system. This study is based upon using technology available in the late 1980's.

In conclusion, we feel that the free-piston Stirling engines are just starting to achieve the attention and creditability that they deserve for space-power application. Free-piston Stirling systems can easily be used with both solar and nuclear powered systems and offer the potential for high efficiency, long life and high reliability.

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- IS A LONG RANGE BROADLY BASED PROGRAM
- SUPPORTS KEY STIRLING TECHNOLOGY AREAS NEEDED FOR:
    - GAS BEARINGS
    - LINEAR ALTERNATORS
    - HEAT EXCHANGERS
    - MATERIALS
    - POWER CONDITIONING INTERFACE
    - OSCILLATING FLOW
    - PERFORMANCE PREDICTIONS

Figure 1. - NASA SP-100 advanced technology program.

- HIGH EFFICIENCY (RELATIVE TO OTHER SYSTEMS)
- POTENTIAL FOR LONG LIFE AND HIGH RELIABILITY
- NON-CONTACTING GAS BEARINGS
- TWO MOVING PARTS
- DYNAMICALLY BALANCED
- NO ROD SEALS
- NO OIL INSIDE ENGINE
- POTENTIAL FOR GRACEFUL DEGRADATION
- POWER OUTPUT FLEXIBILITY

Figure 2. - Why free-piston Stirling?

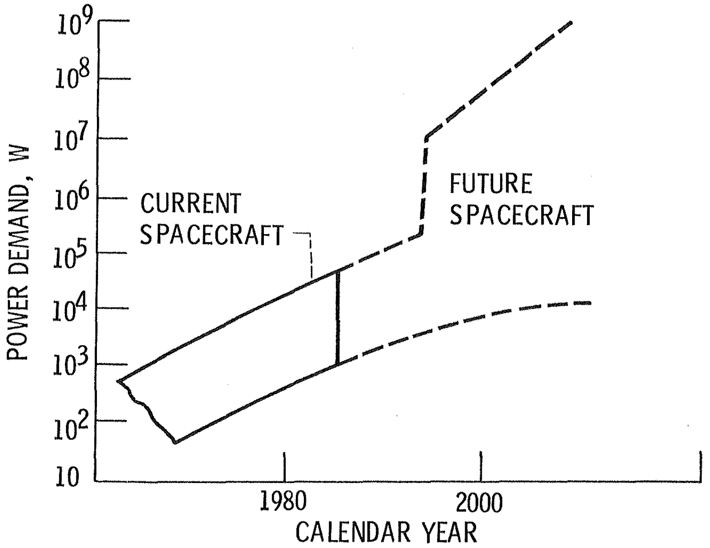


Figure 3. - Planned space power programs address spacecraft growth.

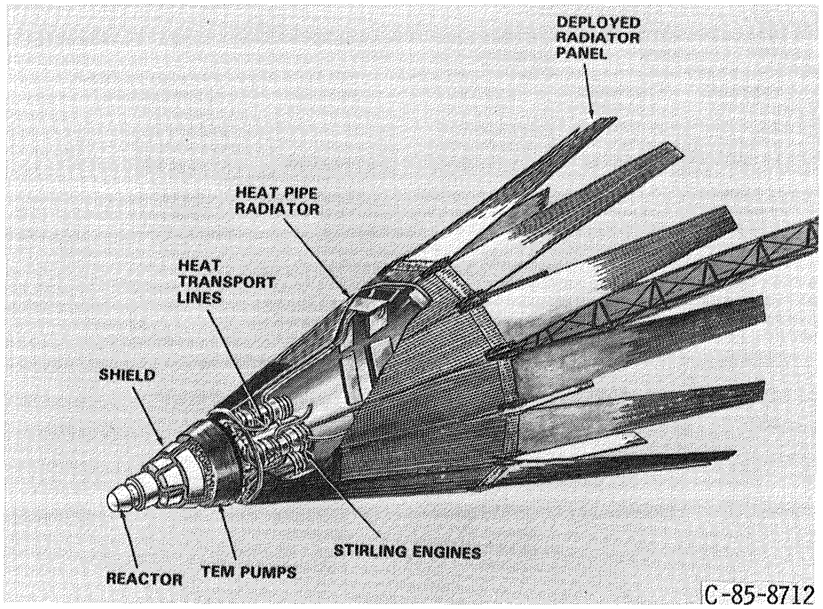


Figure 4. - Artist's conception of SP-100 Stirling system.

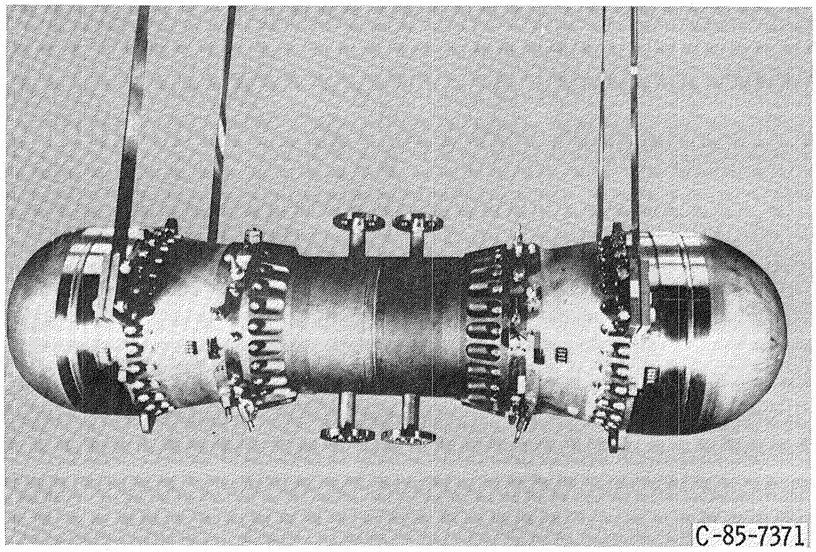


Figure 5. - 25 kWe Space Power Demonstrator Engine (SPDE) at Mechanical Technology Inc.

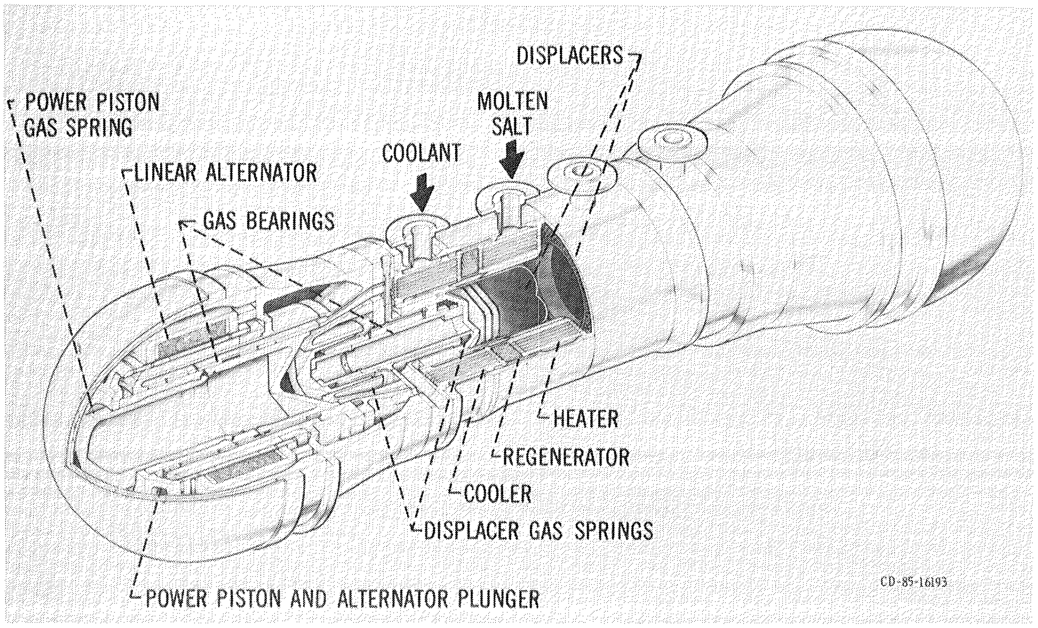


Figure 6. - Space power demonstrator engine.

	GOAL	PERFORMANCE
OUTPUT POWER, kWe	25	6.0
EFFICIENCY, %	25	18-20
TEMPERATURE RATIO	2.0	2.0
T_h-K	650	650
SPECIFIC WEIGHT @25 kWe (kg/kWe)	8.0	12.7 (7.2)*
DYNAMIC BALANCE (CASING AMPLITUDE) mm	.076	.010
GAS BEARING	INTERNALLY PUMPED HYDROSTATIC	EXTERNALLY PUMPED HYDROSTATIC
FREQUENCY, Hz	105	(101)**
MEAN PRESSURE, BAR	150	(150)**
DISPLACER-POWER PISTON PHASE ANGLE, deg	75	75
STROKE, mm	20	20

*WITH MATERIAL SUBSTITUTION AND REPLACING BOLTS AND FLANGES WITH WELDS

**FULL STROKE NOT ACHIEVED AT DESIGN FREQUENCY AND PRESSURE

Figure 7. - Comparison of SPDE design goals to demonstrated performance.

	EXPERIMENTAL		PREDICTED
	INITIAL	RECALIBRATED	
• ELECTRICAL POWER OUT, kWe	6.5	6.0	6.7
• FREQUENCY, Hz	73	73	71
• TEMPERATURE RATIO, T_H/T_C	2.0	2.0	2.0
• PRESSURE, BAR	75	75	75

Figure 8. - SPDE test results at half design pressure - 75 bar.

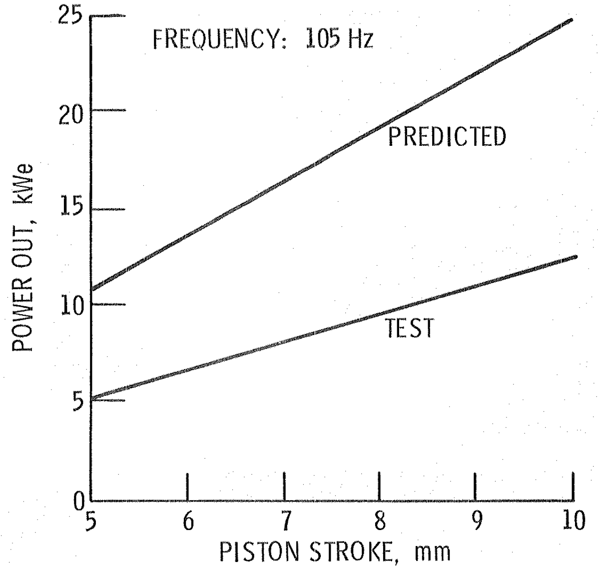


Figure 9. - SPDE power output at 150 bar.

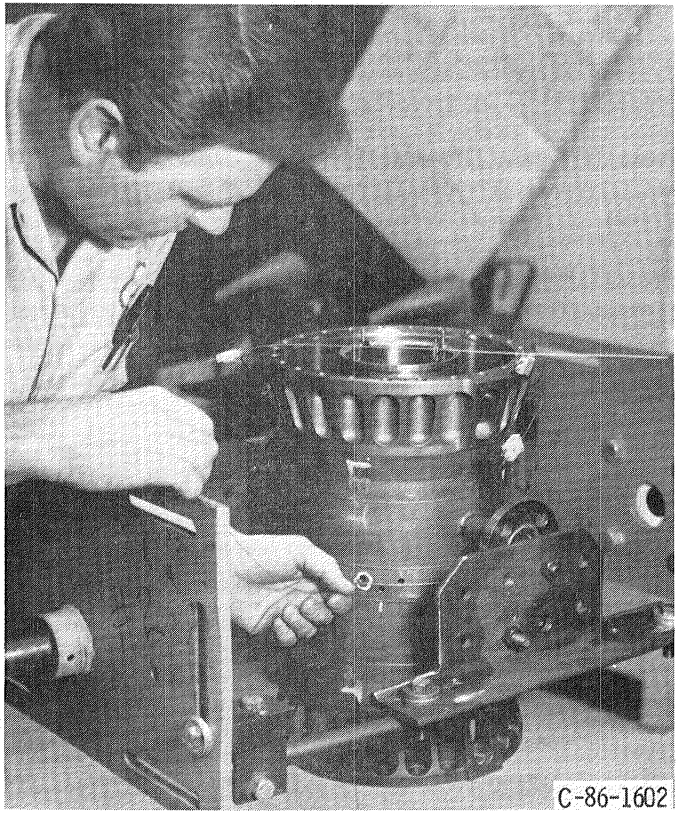
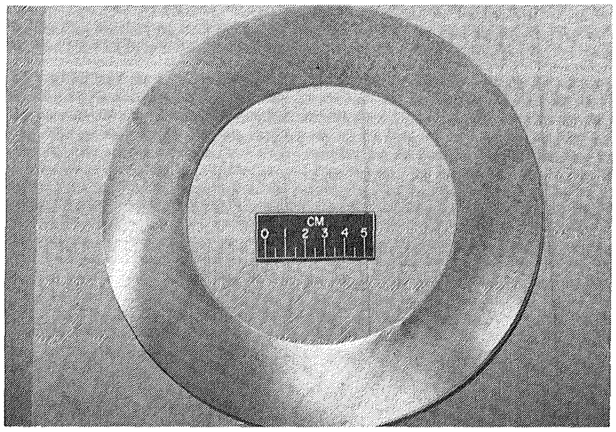
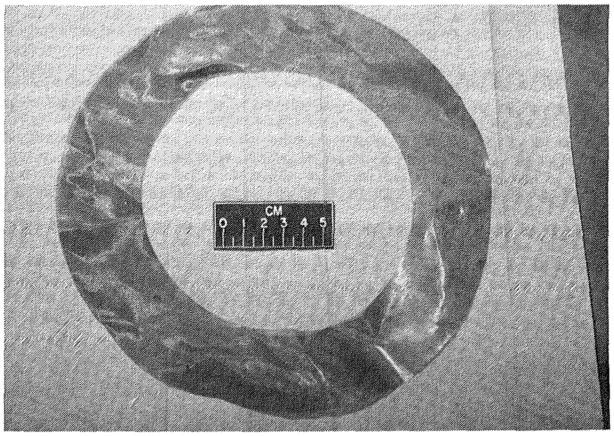


Figure 10. - Installing thermocouples at SPDE heat exchanger interfaces.



BEFORE 105 Hz OPERATION



AFTER 20 HR OF 105 Hz OPERATION

Figure 11. - Comparison of screen regenerators.

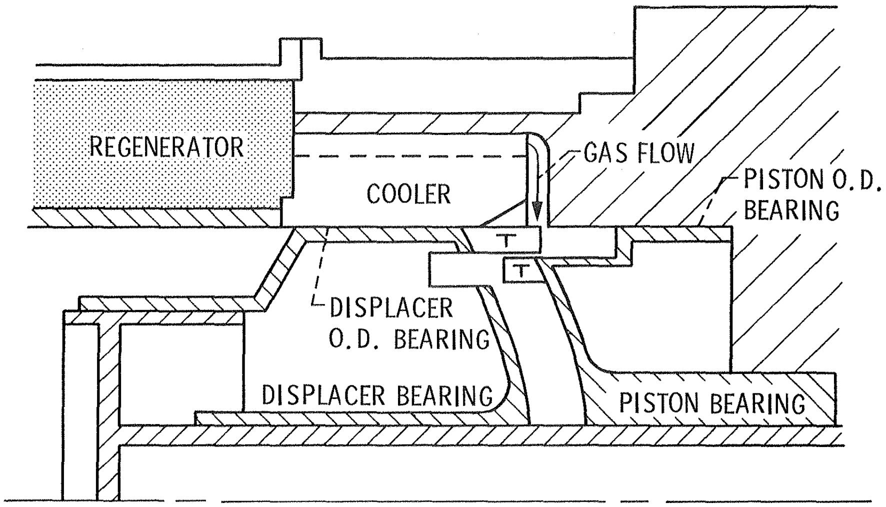
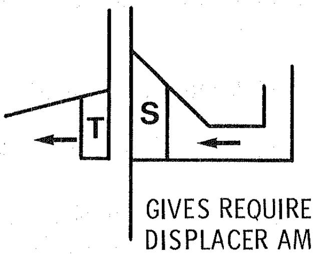


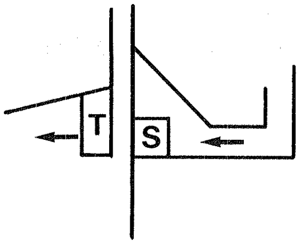
Figure 12. - Spin bearing arrangement in Stirling engine.



FULL PORT STATOR

GAS MUST PASS STATOR GOING BOTH IN AND OUT OF COMPRESSION SPACE

GIVES REQUIRED SPIN RATES BUT CAUSES LOSS OF DISPLACER AMPLITUDE DUE TO FLOW OBSTRUCTION OF STATOR



PARTIAL PORT STATOR

FLOWS THRU STATOR ONLY FOR FLOW INTO COMPRESSION SPACE

UNOBSTRUCTED FLOW OUT OF COMPRESSION SPACE

GIVES REQUIRED SPIN RATES WITH MUCH LOWER FLOW LOSSES - PREFERRED GEOMETRY

Figure 13. - Stator-turbine configuration.

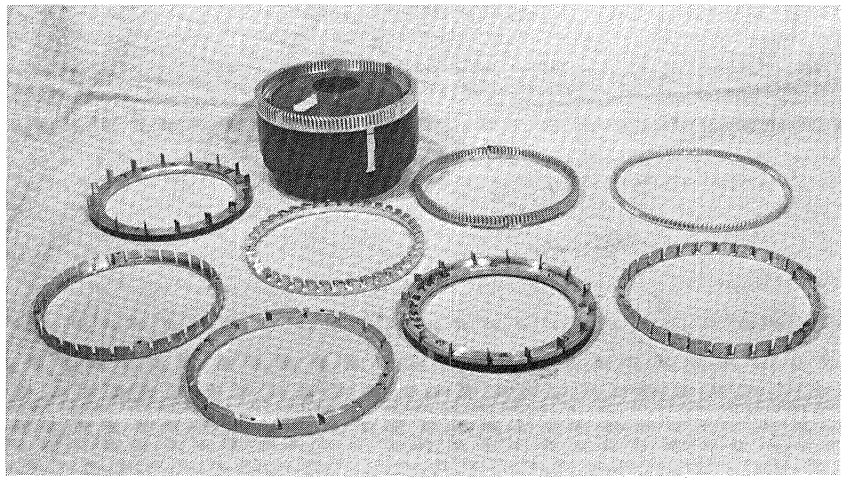


Figure 14. - Representative turbine-stator configurations.

- DEMONSTRATED THAT SPIN BEARING PROVIDES NONCONTACT OPERATION OVER RANGE OF OPERATING CONDITIONS
  - HAVE FOUND NO INSTABILITIES
  - DOES REQUIRE ACCURATE ALIGNMENT AND DIMENSIONAL STABILITY
- DEMONSTRATED SUCCESSFUL STARTUP AND SUSTAINED OPERATION WITH LOW LOSSES - SPIN AT 5 TO 10 Hz
  - BEST FOR PARTIAL STATOR - 128 BLADE TURBINE COMBINATION
  - PARTIAL STATOR MINIMIZES SENSITIVITY TO DISPLACER POSITION AND PHASING
- TESTED VARIETY OF TURBINES AND STATORS OVER RANGE OF AMPLITUDES AND PHASE ANGLES TO DETERMINE DESIGN PARAMETERS

Figure 15. - Hydrodynamic gas bearing summary (for displacer).

CONFIGURATION	SINGLE CYLINDER FPSE WITH LINEAR ALTERNATOR
HEATER MATERIAL	REFRACTORY (NB-1ZR)
HEAT TRANSPORT	PUMPED LIQUID METAL LOOPS
AVERAGE HEATER WALL TEMPERATURE	1080 K
TEMPERATURE RATIO	2.0
LIFE	70 000 hours
ALTERNATOR OUTPUT	25 kWe
PERCENT CARNOT CYCLE EFFICIENCY	57 %
POWER MODULE EFFICIENCY	28.5 %
POWER MODULE SPECIFIC MASS	5.8 kg/kW
OPERATING FREQUENCY	95 Hz
MEAN PRESSURE	176 BAR

Figure 16. - Conceptual design parameters for a space power 25 kWe single cylinder Stirling engine.

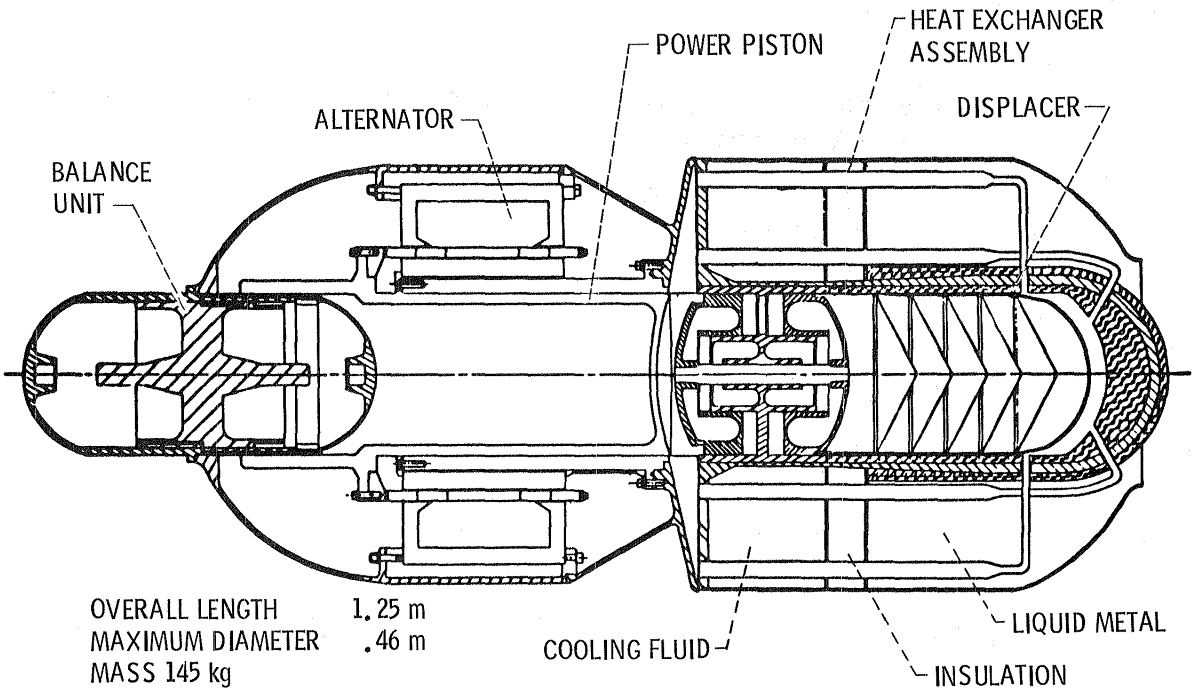


Figure 17. - Space power module.

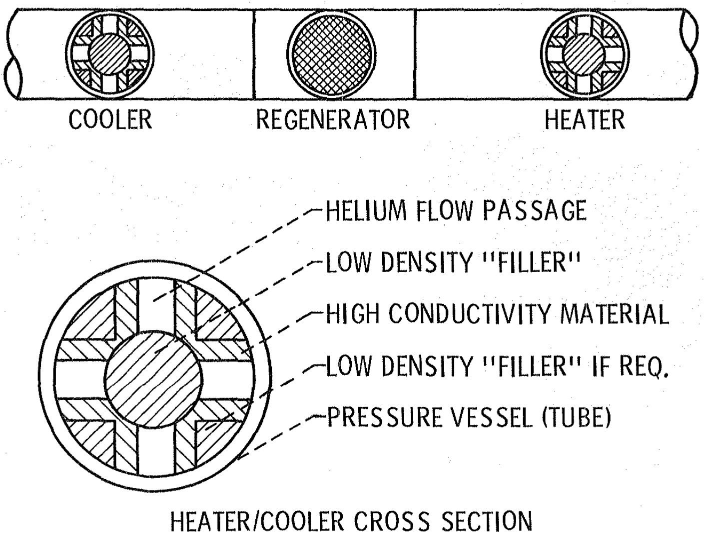


Figure 18. - Typical heat exchanger assembly.

- DETERMINE DESIGN FEASIBILITY OF SINGLE-CYLINDER FPSE-LA IN THE 150 kWe RANGE

- ESTABLISH PARAMETRIC RELATIONSHIPS
  - PERCENT CARNOT CYCLE EFFICIENCY VERSUS SPECIFIC MASS AT TEMPERATURE RATIO AND POWER RANGE

- ASSESS PROMISING ALTERNATIVE STIRLING CONFIGURATIONS

- AWARD OPTIONS
  - REPEAT STUDY FOR ALTERNATE CONFIGURATION
  - CONDUCT DESIGN OF HIGH POWER SYSTEM
  - DETERMINE MAXIMUM POWER; BEYOND 150 kWe

Figure 19. - Space power FPSE scaling study.

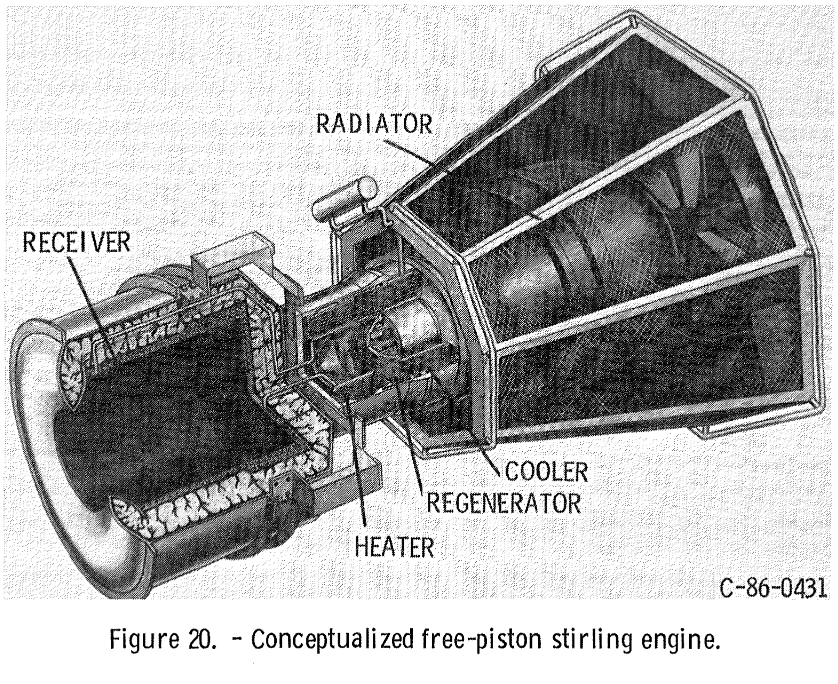


Figure 20. - Conceptualized free-piston stirling engine.

- DEFINE THE ASCS CONFIGURATION
- PREDICT ASCS PERFORMANCE OVER A RANGE OF SOLAR INPUTS
- ESTIMATE SYSTEM AND MAJOR COMPONENT WEIGHT
- DEFINE ENGINE AND ELECTRICAL POWER CONDITIONING CONTROL REQUIREMENTS
- DEFINE KEY TECHNOLOGY NEEDS NOT READY BY THE LATE 1980's IN MEETING GOALS
- PROVIDE A MANUFACTURABILITY AND COST EVALUATION FOR THE ENGINE-ALTERNATOR

Figure 21. - Advanced Stirling conversion system conceptual design objectives.

1. Report No.
NASA TM-87305

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Overview of the 1986 Free-Piston Stirling SP-100
Activities at the NASA Lewis Research Center

5. Report Date

6. Performing Organization Code
506-41-3B

7. Author(s)
Jack G. Slaby

8. Performing Organization Report No.
E-3028

10. Work Unit No.

9. Performing Organization Name and Address
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

11. Contract or Grant No.

13. Type of Report and Period Covered
Technical Memorandum

12. Sponsoring Agency Name and Address
U.S. Department of Energy
Division of Building and Community Systems
Washington, D.C. 20545

14. Sponsoring Agency ~~Code~~Report No.
DOE/NASA/1005-9

15. Supplementary Notes
Final Report. Prepared under Interagency Agreement DE-AI05-82OR1005. Prepared for 21st Intersociety Energy Conversion Engineering Conference, cosponsored by the ACS, SAE, ANS, ASME, IEEE, AIAA, and AIChE, San Diego, California, August 25-29, 1986.

16. Abstract

An overview of the National Aeronautics and Space Administration (NASA) Lewis Research Center SP-100 free-piston Stirling engine activities is presented. These activities include a free-piston Stirling space-power technology feasibility demonstration project as part of the SP-100 program being conducted in support of the Department of Defense (DOD), Department of Energy (DOE), and NASA. The space-power Stirling advanced technology effort, under SP-100, addresses the status of the 25 kWe Space Power Demonstrator Engine (SPDE) including test results. Future space-power projections are presented along with a description of a study that will investigate the feasibility of scaling a single-cylinder free-piston Stirling space-power module to the 150 kW power range. Design parameters and conceptual design features will be presented for a 25 kWe, single-cylinder free-piston Stirling space-power converter. A description of a hydrodynamic gas bearing concept will be presented whereby the displacer of a 1 kWe free-piston Stirling engine is modified to demonstrate the bearing concept. And finally the goals of a conceptual design for a 25 kWe Solar Advanced Stirling Conversion System capable of delivering electric power to an electric utility grid will be discussed. The solar work is under an interagency agreement between DOE/Sandia National Laboratory and NASA Lewis.

17. Key Words (Suggested by Author(s))
Free-piston; Stirling engine; Space power

18. Distribution Statement
Unclassified - unlimited
STAR Category 85
DOE Category UC-96

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of pages

22. Price*
A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161

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