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Overview of NASA Lewis Research Center Free-Piston Stirling Engine Activities

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

Prepared for
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OVERVIEW OF NASA LEWIS RESEARCH CENTER

FREE-PISTON STIRLING ENGINE ACTIVITIES

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ABSTRACT

An overview of the National Aeronautics and Space Administration (NASA) Lewis Research Center (LeRC) free-piston Stirling engine activities is presented. These include (1) a generic free-piston Stirling technology project being conducted to develop technologies generic to both space power and terrestrial heat pump applications in a cooperative, cost-shared effort with the Department of Energy (DOE)/Oak Ridge National Laboratory (ORNL); and (2) a free-piston Stirling space power technology feasibility demonstration project being conducted in support of the Defense Advanced Research Projects Agency (DARPA), DOE, NASA, SP-100 project. The generic technology effort includes extensive parametric testing of a 1 kW free-piston Stirling engine (RE-1000), development of a free-piston Stirling performance computer code, design and fabrication under contract of a hydraulic output modification for RE-1000 engine tests, and a 1000-hour endurance test, under contract, of a 3 kWe free-piston Stirling/alternator engine. The newly initiated space power technology feasibility demonstration effort addresses the capability of scaling a free-piston Stirling/alternator system to about 25 kWe; developing thermodynamic cycle efficiency $\geq$70 percent of Carnot at temperature ratios in the order of 1.5 to 2.0; achieving a power conversion unit specific weight of 6 kg/kWe; operating with noncontacting gas bearings; and dynamically balancing the system.

Planned engine and component design and test efforts are described.

BACKGROUND AND INTRODUCTION

The evolution of free-piston Stirling engines started with the work of Dr. 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 and only two moving components) 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.

As a result, the Department of Energy (DOE) undertook an extensive heat-pump development program. The program guidelines indicate that research and development programs may go as far as laboratory and field experiments for proof-of-concept or principle, or to demonstrate that major technical problems have been solved. One area of specific interest to the DOE is the free-piston Stirling engine-driven heat pump. Coincidentally, NASA, the Lewis Research Center, 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. Some of these requirements include high efficiency, long life, high reliability, hermetically sealed, and very low vibration generation. Considering DOE's interest in free piston Stirling engines for heat pump application and NASA-LeRC's capability (extensive Stirling engine experience and unique test facilities) and interest in space power technology, it became readily apparent that it would be synergistically beneficial to both NASA/LeRC and DOE/ORNL to enter into a cooperative interagency agreement. This was done and an agreement was signed September 23, 1982 between the two agencies. The research resulting from this IAA encompasses generic free-piston technology applicable to both space power and terrestrial heat pump application. A summary of this research will be presented as the first part of this report.

Although this report primarily addresses free-piston Stirling engine activities, 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/JPL Stirling Solar Thermal Project; and (c) managed the Automotive Stirling Engine (ASE) development project. At last year's Eighteenth Intersociety Energy Conversion Engineering Conference (IECEC) Ref. 1 provided an overview of the DOE/NASA ASE program. References 2 to 11 list a series of reports which summarize both NASA directed and NASA conducted kinematic Stirling work.

In early 1983 the SP-100 Program was established through a memorandum of agreement between the Department of Defense (DOD), Defense Advanced Research Projects Agency (DARPA), the National Aeronautics and Space Administration (NASA), Office of Aeronautics and Space Technology (OAST), and the Department of Energy (DOE) Office of Nuclear 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 major technologies to be developed include static and dynamic energy conversion subsystems. One such subsystem is the Stirling power conversion subsystem. Studies show that free-piston Stirling engines are potentially capable of meeting SP-100 mission requirements at low reactor temperatures - a highly desirable feature because it lessens the need for costly advanced reactor development. However, because of the early stage of development of free-piston Stirling engines (the largest successfully demonstrated is only in the 3 kWe range) several technology feasibility issues must be demonstrated before the free-piston Stirling power conversion system can be selected for the SP-100 application.

These technology feasibility issues include:

1. Scaling capability to about 25 kWe from the current 3 kWe level.
2. Developing thermodynamic cycle efficiency $\geq$ 70 percent of Carnot at temperature ratios in the range of 1.5 to 2.0.
3. Achieving power conversion unit specific weight of 6 kg/kWe or less.
4. Operating with noncontacting gas bearings.
5. Dynamically balancing the power conversion unit and -
6. Demonstrating long life and reliability.

The second part of this report describes the research, just getting underway, both analytical and experimental, directed toward addressing the Stirling technology feasibility issues.

Before discussing the research conducted and planned, consider as a practical matter, that free-piston Stirling engines have been only investigated for commercial application over the last 8 to 10 years and total expenditures have been on the order of 10 million - a very modest amount for new engine development. Even at this low total level the technology is advancing rapidly.

FREE-PISTON STIRLING GENERIC RESEARCH

In-house Characterization of a 1 kW Free-Piston Stirling Engine

The RE-1000 engine was purchased under NASA funding and installed in a test cell at the Lewis Research Center. Initial test results and engine description and instrumentation are presented in Ref. 12. The RE-1000, designed and built by Sunpower, Inc., of Athens, Ohio, is an electrically heated, single-cylinder research engine with dashpot load. The engine is pictured in Fig. 1 and is shown schematically in Fig. 2. The 30 hertz engine was designed for helium at a pressure of 70 bar.

The engine with dashpot load is currently being tested under a joint cooperative interagency agreement between NASA and DOE/ORNL. Testing is continuing to update and validate free-piston performance codes with engine test-data. Sensitivity tests are being run to determine the affect of the following on engine performance.

- regenerator porosity variation,
- different displacer rod area,
- piston mass variation, and
- working gas variation.

The RE-1000 engine is a research engine and as such has not been designed for maximum efficiency. Some test results with different engine configurations are shown in Fig. 3. The only differences in engine configuration (e.g., maximum efficiency or maximum power displacer) between the two test conditions are displacer rod area, displacer gas spring stiffness, and damping resulting from different amounts of regenerator material.

Performance Code Validation for RE-1000 Engine

A basic Stirling performance model was originally developed at the Lewis Research Center for a kinematic Stirling engine. This basic model was then adapted and utilized by Mechanical Technology Inc., (MTI) in developing a free-piston Stirling performance model under NASA funding. This free-piston Stirling model is being further developed and validated by NASA using test data generated on the RE-1000 engine. This work also is funded under the joint NASA/LeRC-DOE/ORNL cooperative interagency agreement.

The model in its present form accurately predicts trends in performance. Predicted power and efficiency are in reasonably good agreement with test data within the 10 to 15 percent range. The code can be exercised in either the constrained or unconstrained mode. In the unconstrained mode the only necessary code input is engine pressure, heater temperature, cooling water temperature and load on the dashpot. Figure 4 presents a comparison of unconstrained predicted/experimental results for a typical operating point. Improvements between code predictions and test data are anticipated with planned code modifications which will include improvements in the cooler model and the addition of an appendix gap loss calculation. The model will be later modified to reflect a change in engine configuration from a dashpot load to a hydraulic output and eventually to a gas compressor load. It is these modifications which are of interest for heat pump application.

Hydraulic Output Device for RE-1000 Stirling Engine

Foster-Miller, Inc., (FMI) is under contract to NASA Lewis Research Center with funding provided from DOE/ORNL to develop a hydraulic conversion system for the RE-1000 free-piston Stirling engine.

Free-piston Stirling engines are potentially attractive for a variety of applications and can be adapted to the various applications with several different drive systems. For some applications a hydraulic output offers distinct design advantages. For electric power output a hydraulic drive link could uncouple engine and alternator design criteria and allow use of conventional rotary alternators. Hydraulic drives can of course be used to provide rotary shaft power for a variety of applications. In addition a fairly simple hydraulic link can be used to provide a gas compressor output for heat pump applications.

The FMI contract was directed toward converting the RE-1000 engine with dashpot load into a versatile engine that could be readily converted to either a hydraulic output or simulate a gas compressor output. FMI with Sunpower as a subcontractor completed the mechanical design of a 4-pulse double-acting null band pump under NASA management and funding (13). As part of the NASA-DOE/ORNL interagency agreement, FMI - Sunpower completed design of a complete integrated control system and used unconstrained computer simulations to verify system stability. The computer simulations were used to generate design modifications to convert the 4-pulse pump to a 2-pulse null band pump. To a first order approximation, the 2-pulse pump simulates a double-acting compressor load. Thus the RE-1000 engine can be used for hydraulic and gas compressor output performance investigation. Concurrently, the experimental data will be used to validate the previously discussed FPSE computer code for the hydraulic and gas compressor outputs. A simplified schematic showing the hydraulic output is illustrated in Fig. 5. A diaphragm was chosen as the basic working gas to hydraulic fluid link due to its ease of adaptation, dynamic stability, and low technical risk. Design features are shown in Fig. 6.

FMI will have the hydraulic output device components fabricated. They will assemble, leak test and then deliver it to LeRC where FMI will support system installation, operation, and debugging and analysis of preliminary data. The testing of the hydraulic output device is intended to demonstrate feasibility, efficiency and potential practicality of a hydraulic power system driven by a FPSE. It will result in a validated FPSE code with hydraulic and first-order gas-compressor output. More specific information on the performance advantage of using low hysteresis gas in the bounce space and performance sensitivity to cooling of the power diaphragm will also result.

1000-Hour Endurance Test

Because free-piston Stirling engines are at an earlier phase of development than the kinematic Stirling engine, very little life testing or life potential demonstration testing has been performed. Even though the free-piston Stirling engine is a hermetically sealed unit and has only two moving parts, advocates for space power, heat pump, and other applications requiring long-lived, highly reliable power conversion will remain apprehensive of the free-piston's attractive attributes until engine reliability is demonstrated. The initial step toward demonstrating engine reliability was an endurance test activity successfully completed by Mechanical Technology Inc. (MTI) of Latham, NY. The NASA Lewis Research Center managed this work, under a cooperative interagency agreement. Funding was provided by DOE/ORNL and the Gas Research Institute (GRI).

The specific goal of the program was to accumulate 1000 operational test hours on the nominal 3 kWe gas-fired free-piston Stirling/linear alternator power conversion unit called Engineering Model (EM) shown in Fig. 7. The engine description and details of the operation and inspection of the EM engine over the 1000-hour test run (actually 1100 hours of testing) are documented in Ref. 14. The endurance test duty cycle schedule is shown in Fig. 8. Test result highlights are shown in Fig. 9.

During the testing, the power deviation was less than ±10 percent at 2.5 kWe. The efficiency variation was in the range of ±2.5 efficiency points (nominal engine efficiency about 34 percent defined as electrical energy out divided by heat into the engine). There were two unplanned shutdowns during the course of testing. The first was the need to refurbish the heater head instrumentation. Twenty-seven thermocouples were attached securely. Previously, due to engine vibration, the thermocouples broke loose. New thermocouples were reattached and weights were added to the engine frame to reduce the vibration. The second shutdown resulted when a small segment of the displacer permanent magnet, which had previously broken during preassembly handling, became dislodged and caused the displacer to jam. We feel that neither of these shutdowns adversely reflects upon the success of this endurance test.

One other event deserves mention. At the completion of 400 hours of testing, at the end of the full-stroke full-power test, the engine was run unintentionally for about 3 minutes (about 10 000 cycles) with the hydrostatic gas bearing system inoperative. The engine was shutdown and inspected as soon as this condition was detected. The inspection indicated a number of local scratches attributable to dry-bearing operation. This area exhibited small grooves but no change in outer diameter. In addition, a static flow test through the bearing ports and passages was conducted to determine if bearing clearances changed. No change was apparent and the remainder of the hardware showed no degradation. Testing continued.

At the completion of the endurance testing, it appeared that test load condition did not affect the wear rate since there was no measurable wear. The uncertainty in measurement was 70 millionths of an inch. Critical component measurements were compiled by -

- direct profilometer measurements
- static bearing flow pressure drop
- weight measurements and
- photographs of critical hardware

These tests successfully completed a first step of over 1000 hours of endurance testing on a free-piston Stirling/linear alternator system under various loads and duty-cycle schedules. The engine tested incorporates key design features necessary for long-life and high reliability. One such feature is the hydrostatic gas bearing which eliminates wear between moving parts. Additional test hours are now required for a second step (a 10 000 hr goal) toward establishing the free-piston Stirling engine's long life (50 000 to 100 000 hours) and high reliability for space and terrestrial application. A continuation of testing on this engine for an additional 9000 hours is planned to be funded by the SP-100 program and the Gas Research Institute (GRI).

SP-100 STIRLING ACTIVITIES

Space Power Demonstrator Engine and Issues

Before discussing the SPDE test program it is important to understand why the Stirling system is attractive for space power application. Refer to Fig. 10 and it is easy to see why a Stirling power conversion unit is attractive for a typical SP-100 mission. The system analysis curves indicate that the total mass for an unmanned nuclear-Stirling system producing 100 kW of electrical power is less than 3000 kg, the SP-100 target. This target is achieved for both reactor temperatures of 1000 K and 1100 K and even for a 900 K reactor temperature at (T_H/T_C) temperature ratios below 1.65. This analysis is based on extrapolations of existing free-piston and kinematic Stirling technology. It is these extrapolations which are the key technology issues for free-piston Stirling in the SP-100 application.

One of the key technology issues of free-piston Stirling engines for space power application is high engine efficiency at low engine temperature ratios. Stirling engines long have been known for their high efficiency. In the ASE program, as an example, indicated cycle efficiency in excess of 70 percent of Carnot cycle efficiency is routinely achieved. This occurs at temperature ratios around 3.0. Temperature ratio is defined here as hot metal exterior temperature of the heater (T_H), divided by the cold metal temperature of the cooler exterior (T_C). However, for space application where mass and volume constraints are of paramount importance temperature ratios are required to be in the range of 1.6 to 2.0. This means that the temperature difference between heater and cooler is reduced considerably; and the issue must be addressed as to whether the high percent of Carnot cycle efficiency can be maintained at the lower T_H/T_C temperature ratios. This is but one of the feasibility issues which we hope to resolve as a result of the Space Power Demonstration Engine (SPDE) activity.

Free-piston Stirling technology is currently in engineering development and before Stirling systems can be selected for SP-100 application, technology issues must be resolved by component and system tests. The SPDE program will attempt to substantiate experimentally the potential that Stirling shows in system analysis comparisons. The objective of the SPDE program which will be conducted at Mechanical Technology Inc. of Latham, NY, is to design, build and demonstrate with actual hardware all the key technology issues that will permit selection for SP-100 application. The key technology issues that will be demonstrated in this program are shown in Fig. 11.

It is to be noted that the SPDE test is to be conducted at T_H = 650 K and T_C = 325 K, rather than at the expected application temperatures (T_H = 1100 K, T_C = 550 K). This is being done to provide meeting increased confidence in the time constraint imposed by the SP-100 engineering development decision date of July, 1985. The higher temperature would require a liquid metal heat source loop whereas a more conventional heat source system can be utilized at the lower temperatures. A liquid metal loop would significantly increase design, fabrication, and tests schedules. Furthermore, operation at the higher temperature is not considered to be a key technology issue. Keep in mind that the ASE program has logged about 10 000 hours of engine testing for component evaluation at temperatures around 1100 K with very good reliability.

In addition the MTI design is expected to be capable of operation at 900 K for approximately 1000 hours, providing an option for testing at this temperature, once the feasibility demonstration tests are complete. Finally, preliminary designs will evaluate what modifications would be necessary to upgrade the SPDE to operate at T_H = 1100 K and T_C = 550 K, and to indicate how the final system will achieve a specific weight of 6 kg/kWe.

The risk in building and testing the SPDE is not great. A schematic of one cylinder of the two cylinder engine is shown in Fig. 12. The engine is composed of two opposed 12.5-kW engines to achieve dynamic balance. This approach is similar to that incorporated into a military advanced development model also designed and built by MTI. Power has been scaled from the present 3 kWe (as used for the 1000 hour endurance test) model to 12.5 kWe (per cylinder) so that the power extrapolation is only approximately 1 to 4. Specific weight goals will be achieved by increasing both pressure and frequency. Pressure is increased to the value used in the ASE program, 150 bar, and the frequency is doubled to 120 Hz. Critical thermodynamic parameters have been maintained within existing engine experience. The alternator configuration uses a samarium cobalt permanent magnet plunger similar to the MTI designed military engine.

Continuation of Endurance Testing to 10 000 Hours

The objective of this test is to extend the nominal 1000-hour (1100 actual hr run) endurance test time on the MTI 3 kWe Engineering Model engine to 10 000 hours. This engine incorporates the same design features necessary for long life and high reliability that are found in the SPDE design. Project Management will be supplied by the Lewis Research Center with funding provided by the SP-100 program and GRI. This test will be conducted at 700° C (973 K) heater temperature at full piston stroke. The heater head will be dimensionally inspected to establish creep history during testing. These measurements will be repeated at about 500-hour intervals. Bearing clearances also will be evaluated by a flow check (when the engine is not operating) where the flow versus pressure characteristic is measured. Internal measurements will be repeated should any failures necessitate an engine rebuild. Also interval measurements will be taken before and upon completion of the testing. The engine operating conditions are summarized in Fig. 13. To more closely simulate zero "g" conditions the engine will be mounted with the piston motion vertical. A new piston and cylinder will be installed to improve engine performance by having reduced clearances. This also will reduce the amount of bearing gas flow and improve engine performance.

The extension of the 1000-hour endurance test for the SP-100 program emphasized the similarity in Stirling engine requirements for applications such as space power and heat pumps. The original program was a joint effort between NASA, DOE/ORNL, and GRI. The SP-100 program, with GRI support, is continuing this important milestone needed for establishing free-piston Stirling reliability.

Design of 25 kWe Stirling Space Power Sub System For Temperature Ratio of 1.65/1

Concurrent with the SPDE program, Sunpower, of Athens Ohio will prepare the preliminary design of a space power module with a T_H = 875 K and a T_H/T_C = 1.65. The optimized design will incorporate a patented spin-lubricated hydrodynamic gas bearing and will be based upon the requirements listed in Fig. 14.

Prior to conducting the design, Sunpower will perform a conceptual review of conventional free-piston linear-alternator configurations as well as alternative concepts - some of which include FPSE's with hydraulic output and rotating alternator; and with a gas turbine and rotating alternator. Sunpower will recommend for NASA approval which system shall be selected for the design effort.

To aid in the design of the space power module, Sunpower will conduct parametric sensitivity studies for optimized designs at three different T_H/T_C temperature ratios of 1.5, 1.75, and 2.0. These studies will concentrate on the critical relationships between power module specific weight and percent of Carnot cycle efficiency as a function of T_H/T_C. This will be done for a T_H of 875 and 1075 K (heater head temperatures) corresponding to reactor outlet temperatures of 900 and 1100 K. Thus six cases will be investigated. Each case will be optimized to obtain maximum system efficiency and minimum specific weight.

The design procedure will incorporate initial scaling to generate general engine size, configuration and weight. Optimization programs will be used for coarse and fine tuning of the designs. Since the space power module may operate at frequencies above 60 Hz, Sunpower will use experimental data from an ocillating test rig as well as a thorough review of operating engine test results to insure that the pressure drop correlations for the heat exchanger loop employed in the computer codes reflect the actual engine behavior.

The two cylinder SPDE engine is dynamically balanced as a result of the opposing pistons and displacers. However, if this study shows a single/cylinder engine to be more advantageous, then another approach to dynamic balancing must be employed. One such approach is the design of a dynamic absorber for the engine. A single absorber is preferred, but a double mass absorber would allow for a wider range of operating frequencies. To investigate dynamic balancing of a single cylinder free-piston Stirling engine NASA will have Sunpower design, fabricate, and assist in the installation and testing of a balancing system for the single cylinder RE-1000 engine at NASA Lewis.

This Space Power Module design will also incorporate the use of spin-lubricated noncontact hydrodynamic gas bearings for both the displacer and power pistons. Sunpower will evaluate these gas bearings on a separate test rig. The hydrodynamic gas bearings and this test rig evaluation are described in the following section.

Spin-Lubricated Hydrodynamic Gas Bearing Evaluation

Sunpower, as a part of the contract to design a 25 kWe space power module, will analytically and experimentally assess the feasibility of a patented spin-lubricated noncontacting hydrodynamic gas bearing system as a means to achieve long life and high reliability for the two moving components (displacer and piston) in a Stirling space power module design.

The concept incorporates the interaction of existing gas flow through the compression space with a turbine mounted on the displacer. The turbine consists of simple grooves on the cold end of the the displacer. This concept also should apply equally well to the linear alternator plunger (piston). The turbine as shown in Fig. 15 encounters the flow only at the outermost part of the displacer stroke (away from the hot end) where the gas flow to the compression space is a maximum. Thus the torque is applied to the displacer in a unidirectional manner. This slight torque is adequate to maintain a constant angular velocity and a gas film between the displacer and its center rod.

The experimental demonstration will include operating parameters and approximate dimensions compatible with the space-power module design. This demonstration will be conducted at room temperature and show that the desired operating conditions (approx 530 K) can be extrapolated from these results.

A test rig will be designed and built to simulate the operating conditions. Instrumentation will be included to measure component rotational speed and running clearances and to give an indication of contact if it occurs. Modifications will be made if necessary and retesting done until the goal of noncontact operation is achieved.

Lightweight Linear Alternators for Free-Piston Stirling Engine Space-Power Systems

In early January 1984 NASA awarded a contract to Energy Research and Generation of Oakland, California to develop and demonstrate a lightweight linear alternator concept. The proposed alternator is a synchronous linear machine which operates equally well as a motor. Technical objectives include the design, fabrication, testing and demonstration of a lightweight, high efficiency, compact linear alternator for FPSE Space power conversion systems. The feasibility, limitations and potential of the proposed alternator concept will be assessed through analyses and testing to determine the objectives shown in Fig. 16.

Two versions of the linear alternator (LA) will be designed; and each will generate an output voltage by reversing the magnet flux that couples each stator coil as the armature magnets move across the stator poles faces.

In the first version the entire flux produced by a magnet pair couples with each coil, whereas in the second version only one-half this flux couples with each coil. As a result, the voltage generated in each coil is only one-half that of the first version, therefore using twice the number of coils connected in series to equal voltage output of the first version. The principle difference in flux leakage between the two configurations is due to axial flux leakage between stator sections. If this flux leakage is small then the first version is lighter and exhibits only half the I^2R loss of the second version, assuming both have equal size and output.

The design effort will be conducted by first varying design parameters such as: stroke, magnet diameter and thickness, coil dimensions, pole-to-stroke ratio, and reciprocating frequency for each of the two LA versions. Results so obtained will provide performance trade-offs such as efficiency versus weight, size, stroke, and reciprocating frequency. A preferred design for each of the two LA configurations will be selected for an electric power output of approximately 3 kW.

CONCLUDING REMARKS

The free-piston Stirling projects conducted at the Lewis Research Center, (through both in-house and contract activities), encompass free-piston Stirling technology; computer code generation and validation; design, fabrication and test of a 25 kWe Space Power Demonstration Engine; and research and development directed toward terrestrial heat pump and space power application. Current hardware test programs extend from 1 kW through 25 kW engine output. These experimental power conversion investigations cover linear alternator, hydraulic, and gas compressor output. Stirling technology feasibility issues being addressed include scalability, dynamic balancing, minimizing specific weight, achieving high efficiency at temperature ratios less than 2.0, demonstrating long life and high reliability, evaluating gas bearing systems, verifying computer codes, and investigating advanced lightweight linear alternator concepts.

Funding has been provided by government agencies as well as private industry. Funding organizations include NASA, DOE, DOD, and GRI. The common and complementary requirements of the various applications along with the fine cooperation of the funding organizations have allowed these activities to be carried on in a cost-effective, cooperative manner. The net result is a well integrated free-piston Stirling engine technology effort that addresses both synergistic and specific requirements of various applications.

The research and development efforts discussed in this report will advance the technology and provide more definitive answers as to the status and potential of free-piston Stirling engines for applications such as SP-100, terrestrial heat pumps, and space station power systems. System studies have shown dramatically that free-piston Stirling systems have significant advantages compared to competing alternative systems. It is now time to demonstrate with hardware that the promise of high reliability, long life, high efficiency, and lightweight components are indeed achievable.

REFERENCES

1. D. G. Beremand, "DOE/NASA Automotive Stirling Engine Project Overview '83.," DOE/NASA/51040-48, NASA TM-83405, (1983).

2 "Automotive Stirling Reference Engine Design Report," MTI 81ASE164DR2, Mechanical Technology, Inc., (DOE/NASA/0032-12, NASA CR-165381), (1981).

3. "Automotive Stirling Engine Mod I Design Review Report," MTI 81ASE142DR1, Mechanical Technology, Inc., (DOE/NASA/0032-16, NASA CR-167935), MTI (1982).

4. "Automotive Stirling Engine Development Program," MTI 83ASE334SA4, Mechanical Technology, Inc., (DOE/NASA/0032-21, NASA CR-168205), (1983).

5. W. P. Teagan, D. R. Cunningham, "Stirling Engine Application Study," DOE/NASA/0254-1, NASA CR-168087 (1983).

6. M. A. White, "Conceptual Design and Cost Analysis of Hydraulic Output Unit for 15kW Free-Piston Stirling Engine," DOE/NASA/0212-1, NASA CR-165543 (1982).

7. S. Holgersson, W. H. Percival, in Proceedings of the Twentieth Automotive Technology Development Contractors' Coordination Meeting, p. 7, SAE, Warrendale, Pa., (1983).

8. J. G. Slaby, "Overview of a Stirling Engine Test Project," DOE/NASA/1040-80/12, NASA TM-81442 (1980).

9. G. G. Kelm, J. E. Cairelli, R. J. Walter, "Test Results and Facility Description For a 40-Kilowatt Stirling Engine," DOE/NASA/51040-27, NASA TM-82620 (1981).

10. D. C. Johnson, C. W. Congdon, L. L. Begg, E. J. Britt, L. G. Thieme, "Jet Implingement Heat Transfer Enhancement for the GPU-3 Stirling Engine," DOE/NASA/51040-33, NASA TM-82727 (1981).

11. R. J. Meijer, B. Ziph, "Evaluation of the Potential of the Stirling Engine for Heavy Duty Application," NASA CR-165473 (1981).

12. J. Schreiber, "Testing and Performance Characteristics of a 1-kW Free-Piston Stirling Engine," NASA TM-82999 (1983).

13. W. M. Toscano, A. C. Harvey, K. Lee, "Design of Hydraulic Output Stirling Engine," NASA CR-167976 (1983).

14. G. Dochat, J. Rauch, G. Antonelli, "Free-Piston Stirling Engine Endurance Test Program," Twenty-first Automotive Technology Development Contractors Coordination Meeting, Dearborn, MI 11/14/83, (1983).

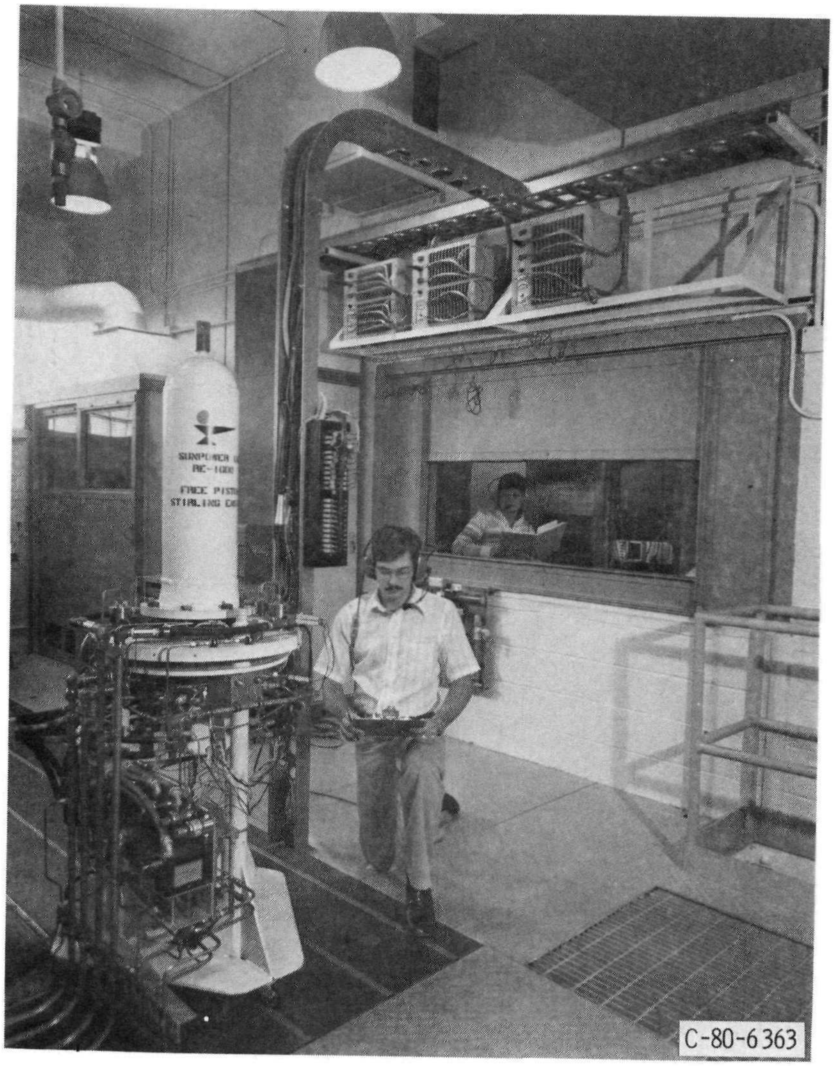

Figure 1. - RE-1000 free-piston Stirling engine.

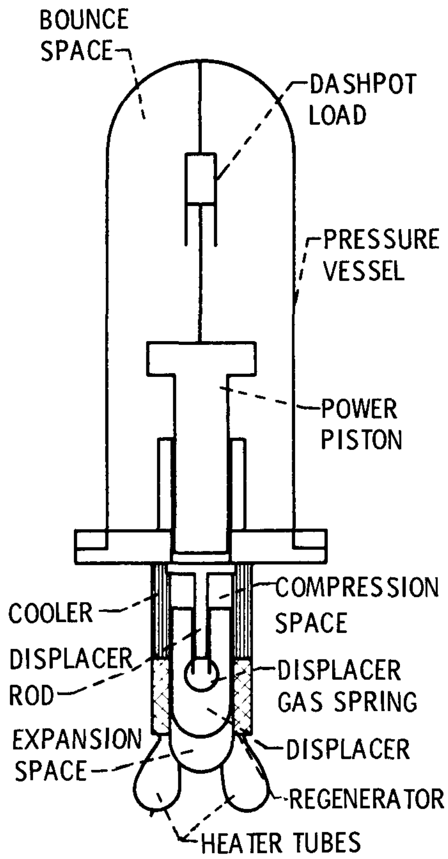

Figure 2. - Component layout of RE-1000 free-piston Stirling engine.

ENGINE CONFIGURATION	POWER, W	*EFFICIENCY, PERCENT
MAXIMUM EFFICIENCY DISPLACER, NOMINAL REGENERATOR AND DISPLACER GAS SPRING	1250	33.0
MAXIMUM POWER DISPLACER, LESS REGENERATOR MATERIAL, STIFFER DISPLACER GAS SPRING	1500	24.3

*EFFICIENCY DEFINED AS ENGINE SHAFT POWER DIVIDED BY HEAT INTO THE HEATER TUBES

Figure 3. - RE-1000 free-piston Stirling performance.

	FREQUENCY, Hz	BRAKE EFFICIENCY, PERCENT	OUTPUT POWER, W	PHASE ANGLE, deg
EXPERIMENTAL	30.4	29	983	50.8
PREDICTED (UNCONSTRAINED)	30.2	33	1097	47.1

Figure 4. - RE-1000 engine performance - predicted versus experimental

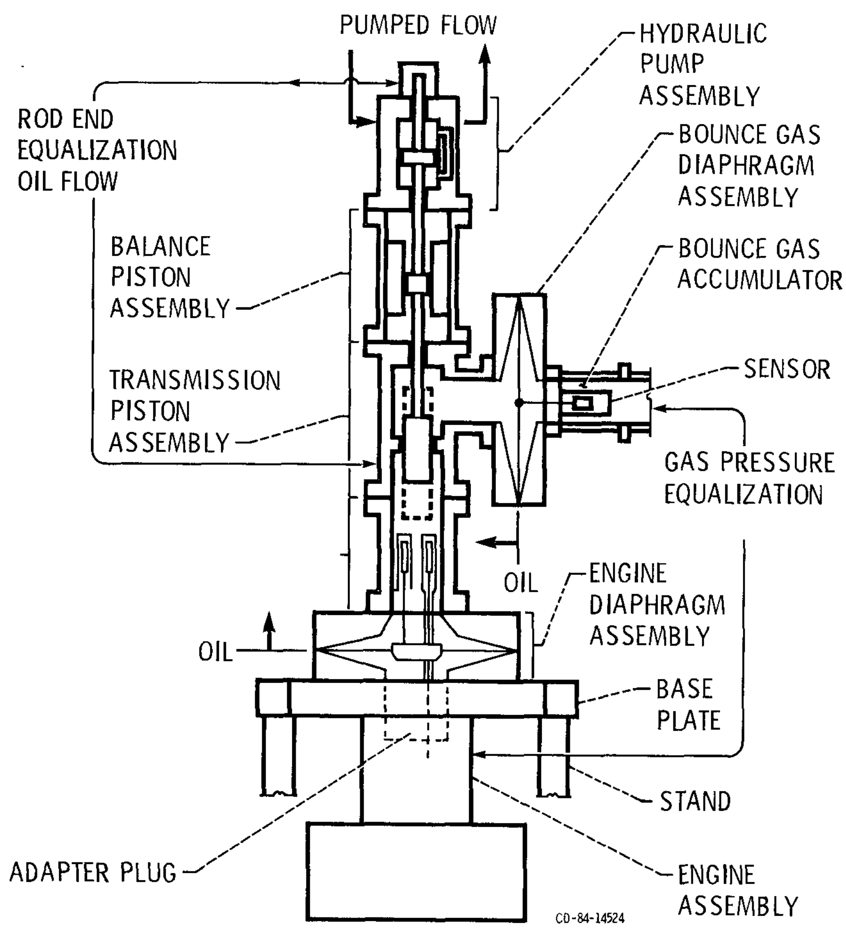

Figure 5. - Simplified schematic of the hydraulic output system design.

- MODULAR SECTIONS AND SIMPLE, ACCESSIBLE PARTS FOR RESEARCH TESTING
- INTERCHANGEABILITY WITH CURRENT RE-1000 FPSE OUTPUT SECTION WITHOUT DISTURBING ENGINE SECTION
- EITHER VERTICAL AXIS HYDRAULIC ASSEMBLY OR HORIZONTAL ASSEMBLY TO DEMONSTRATE BETTER DYNAMIC BALANCING
- DISPLACEMENT SENSORS ON ALL ENGINE MOVING PARTS AND HYDRAULIC PUMP
- CONSERVATIVE DESIGN FOR LOW STRESS AND LOW COST
- PUMP UNIT MODIFIED TO ALLOW HEAT PUMP COMPRESSOR LOAD SIMULATION
- FLEXIBILITY OF USING LOW HYSTERESIS GAS IN BOUNCE SPACE
- ABILITY TO ASSESS PERFORMANCE SENSITIVITY OF POWER DIAPHRAGM COOLING

Figure 6. - Summary of important features of hydraulic output device.

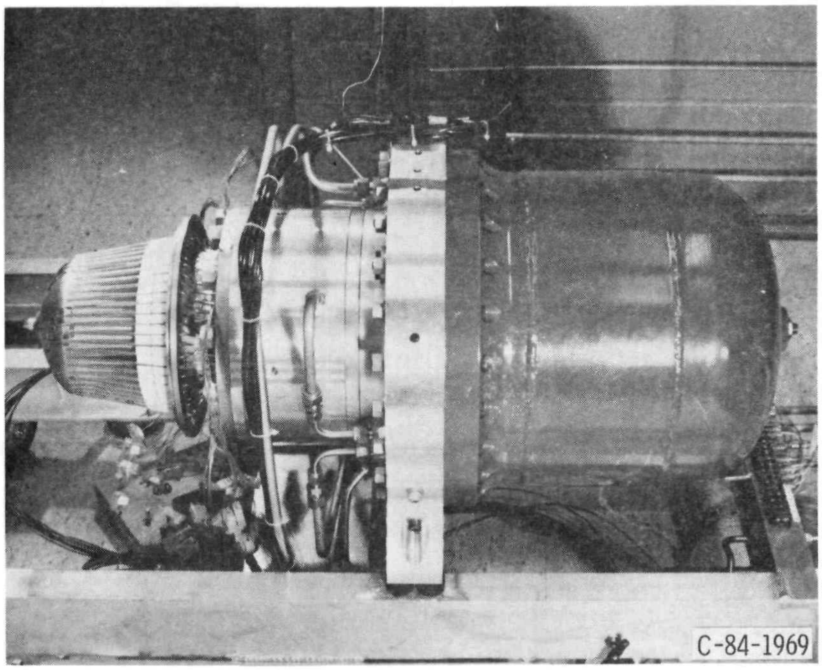

Figure 7. - 3kW$_\ell$ Mechanical Technology Inc. free-piston Stirling/Linear alternator engineering model engine.

- 100 hr LOW POWER~700 W; 1/2 STROKE
- 300 hr FULL STROKE - FULL POWER
- 700 hr DUTY CYCLE
- 250 DRY START-STOPS WITH SELF CONTAINED GAS BEARING SUPPLY

Figure 8. - Endurance test duty cycle schedule.

THROUGHOUT TESTS

POWER DEVIATION < ±10 PERCENT

EFFICIENCY VARIATION < ±2.5 EFFICIENCY POINTS

UNPLANNED SHUTDOWNS

HEATER REFURBISHED FOR THERMOCOUPLES

BROKEN DISPLACER PERMANENT MAGNET SEGMENT CAME LOOSE

TEST LOAD CONDITION DID NOT AFFECT WEAR RATE OR PERFORMANCE

NO MEASURABLE WEAR

UNCERTAINTY, 70 MILLIONTHS OF in.

FLOW TESTS, 50 MILLIONTHS OF in.

Figure 9. - Endurance test results.

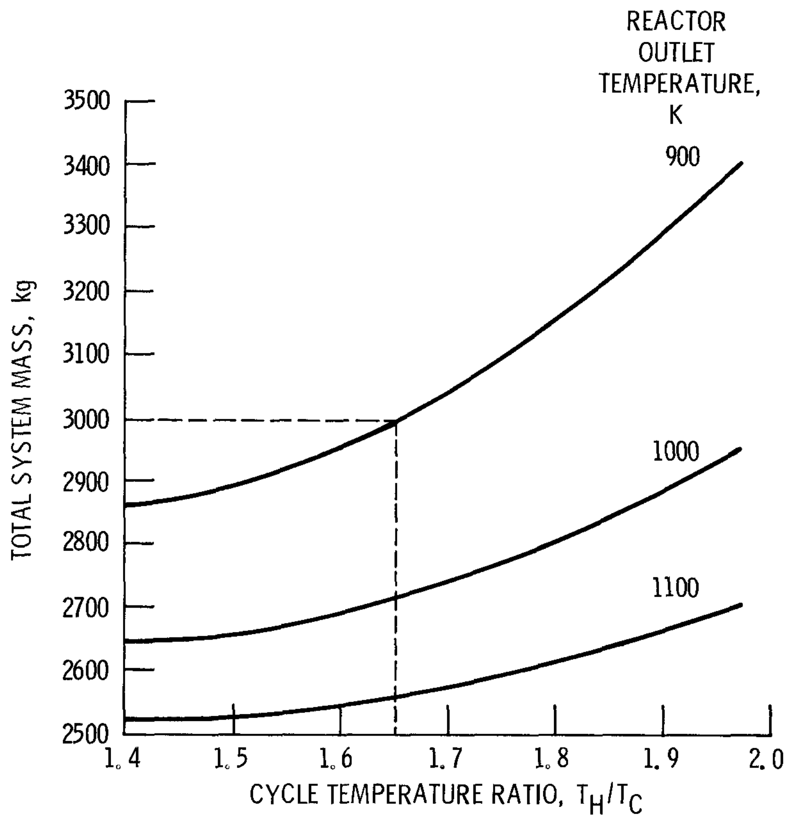

Figure 10. - Unmanned Stirling system mass versus cycle temperature ratio. Engine-alternator specific mass, 6.0 kg/kWe; 5, 25-kWe Stirling engines; efficiency, 64 percent carnot.

THE SPDE WILL DEMONSTRATE

- SCALING → 25 kWe (3 kWe/P - 12.5 kWe/P)
- CODE VERIFICATION -- SCALING
  -- FREQUENCY, PRESSURE
  -- LOSS MECHANISMS, PERFORMANCE AT $T_R = 2$; $T_H = 650$ K
- OVERALL SYSTEM EFFICIENCY 25 PERCENT; THERMODYNAMIC CYCLE EFFICIENCY = 67 PERCENT OF CARNOT
- SPECIFIC WEIGHT 8 kg/kWe (INITIAL) → 6 kg/kWe
- HYDROSTATIC GAS BEARINGS (POTENTIAL FOR VERY LONG LIFE)
- DYNAMIC BALANCE

DEMONSTRATION TESTS AT T_H/T_C = ~650 K/325 K (TIME, COST)

ENGINE DESIGNED FOR 1000 hr OPERATION AT 900 K AFTER FEASIBILITY DEMONSTRATION TESTS

ANY POTENTIAL CRITICAL TECHNOLOGICAL LIMITATIONS WILL BE IDENTIFIED

DESIGN MODIFICATIONS AND COSTS WILL BE IDENTIFIED FOR OPERATION AT:

1100 K/550 K, 1100 K/550 K (CLA), 1100 K/325 K

Figure 11. - MTI Space Power Demonstration Engine (SPDE).

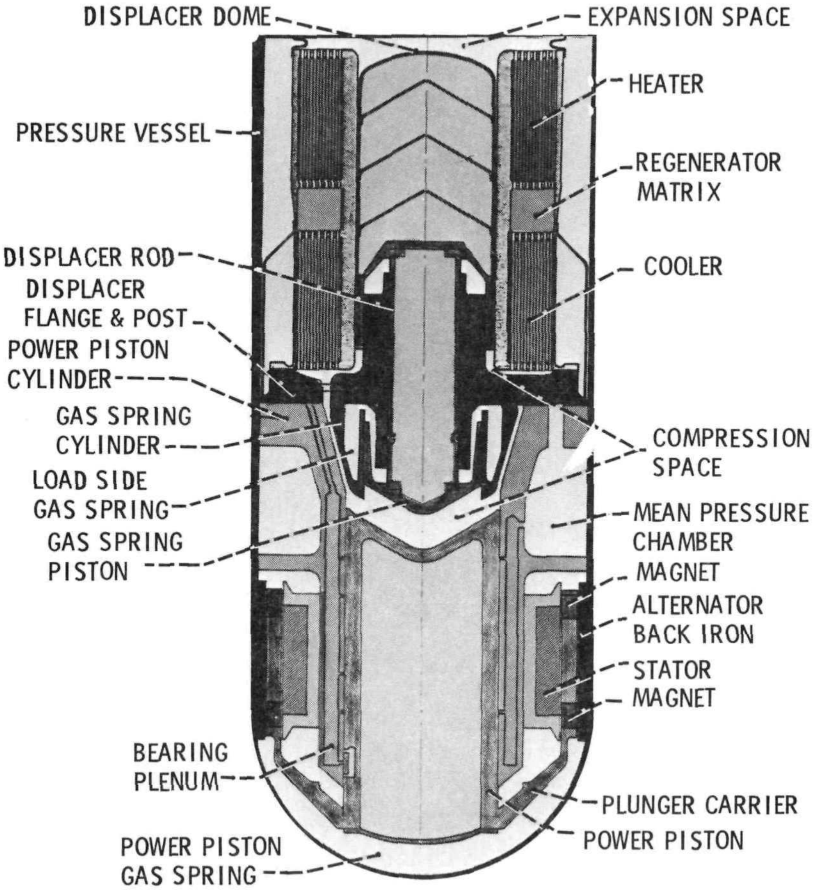

Figure 12. - One cylinder of space-power demonstrator engine.

HEATER HEAD TEMPERATURE	973 K
FREQUENCY	60 Hz
MEAN PRESSURE	62 bar
PISTON STROKE	20 mm
ELECTRICAL OUTPUT POWER	1.5 - 2.5 kWe
DUTY CYCLE	FULL STROKE CONTINUOUS
GAS BEARINGS	SELF-PUMPED HYDROSTATIC

Figure 13. - 10 000 hr Endurance test conditions.

SUNPOWER

- PARAMETRIC ENGINE DESIGNS

  IDENTIFY MINIMUM SPECIFIC WEIGHT AND OPTIMUM EFFICIENCY

  T_H/T_C = 2.0, 1.75, 1.50, T_H = 1075, 875 K

- INDEPENDENT DESIGN OF 25 kWe MODULE

  T_H/T_C = 1.65, T_H = 875 K, T_C = 530 K

  HYDRODYNAMIC GAS BEARINGS

  $\leq$ 6 kg/kWe

  DYNAMIC BALANCE

  COMPATIBLE WITH POTENTIAL HEAT TRANSPORT SYSTEMS FOR 7-10 yr LIFE

  ANY POTENTIAL LIFE LIMITING TECHNOLOGIES WILL BE IDENTIFIED

- DEMONSTRATION OF HYDRODYNAMIC GAS BEARINGS

  COMPATIBLE WITH ABOVE DESIGN

  ROOM TEMPERATURE DEMONSTRATION

  SHOW EXTRAPOLATION TO 530 K

- DYNAMIC BALANCE OF LEWIS'S SINGLE PISTON RE-1000 ENGINE

ERG

- INVESTIGATE CONCEPTS FOR ADVANCED LIGHTWEIGHT LINEAR ALTERNATOR

Figure 14. - Elements of sunpower and ERG Stirling engine contracts.

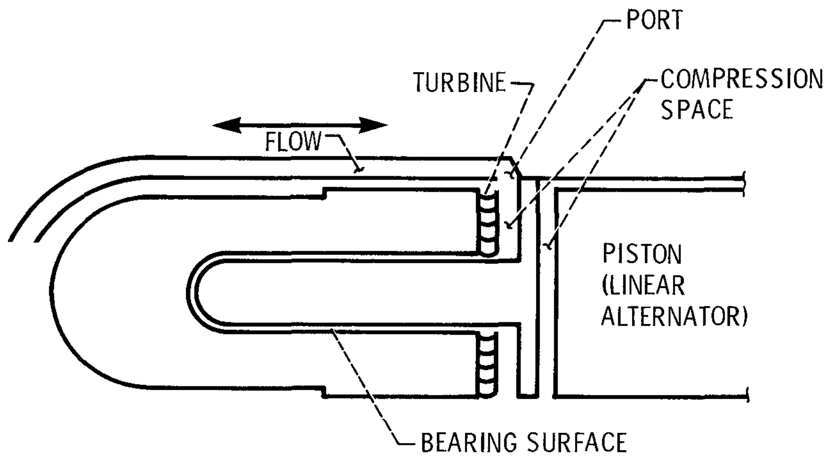

Figure 15. - Spin lubricated bearing technique. (Displacer passes port when flow is to compression space.)

TO DETERMINE -

SPECIFIC WEIGHT AS A FUNCTION OF EFFICIENCY, SIZE, AND FREQUENCY

CONTROLABILITY

VOLTAGE WAVEFORM AND ALTERNATOR EFFICIENCY AS A FUNCTION OF LOAD

COST EFFECTIVENESS

Figure 16. - ERG lightweight linear alternator study objectives.