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Overview of Free-Piston Stirling Technology at the NASA Lewis Research Center

Jack G. Slaby
National Aeronautics and Space Administration
Lewis Research Center

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

Prepared for
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ABSTRACT

AN OVERVIEW of the National Aeronautics and Space Administration (NASA) Lewis Research Center (Lewis) free-piston Stirling engine activities is presented. These activities include; (1) a generic free-piston Stirling technology project being conducted to develop technologies synergistic 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 demonstration project as part of the SP-100 program being conducted in support of the Department of Defense (DOD), DOE, and NASA/Lewis. The generic technology effort includes extensive parametric testing of a 1 kW free-piston Stirling engine (RE-1000), development and validation of a free-piston Stirling performance computer code, and fabrication and initial testing of an hydraulic output modification for the RE-1000 engine. The space power technology effort, under SP-100, addresses the status of the 25 kWe Space Power Demonstrator Engine (SPDE) including early test results.

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 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, potential for long life and high reliability, low vibration, and hermetically sealed. These common requirements became the basis for a cooperative interagency agreement between DOE/Oak Ridge National Laboratory (ORNL) and NASA/Lewis signed Sept. 1982. The research resulting from this IAA covers generic free-piston Stirling technology applicable to both space power and terrestrial heat pump application. This report discusses some of the generic Stirling technology resulting from this IAA.

In 1983 the SP-100 Program was established through a memorandum of agreement between the DOD, NASA and the DOE 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 the NASA Lewis in support of the SP-100 is also discussed as part of this report.

Both areas of development, the generic Stirling technology resulting from the NASA/DOE space power/heat pump work and the triagency SP-100 work, are outlined in Fig. 1.

In addition to the SP-100 and DOE/ORNL-NASA/Lewis projects there is currently under negotiations, an IAA between DOE/Sandia National Laboratory, and NASA/Lewis to utilize Stirling space technology for solar thermal terrestrial application for generating solar-derived electrical power.

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/Jet Propulsion Laboratory (JPL) Stirling Solar Thermal Project; and (c) managed the Automotive Stirling Engine (ASE) development project. Reference 1 provides an overview of the DOE/NASA, ASE program. References 2 to 13 list a series of reports which summarize both NASA directed and NASA conducted kinematic Stirling work.

Before discussing the research and development work on free-piston Stirling engines, consider as a practical matter, that free-piston Stirling engines have been investigated for commercial applications only over the past 15 yr and total expenditures have been on the order of less than 30 million dollars - a very modest amount for new engine development. Even at this low total level, the technology is advancing rapidly.

FREE-PISTON STIRLING BACKGROUND AT NASA LEWIS

Around 1978 the NASA Lewis free-piston Stirling engine technology effort was started with modest funding by the NASA Conservation and Fossil Energy Systems Branch of the Energy Systems division. This NASA-funded effort was aimed at broadening the general Stirling engine technology base at Lewis and assessing its applicability to a variety of applications. The work described in this report has relied heavily on capabilities and information developed at Lewis under various DOE, DOD, and NASA funded activities. The free-piston Stirling engine is at an earlier state of development than the kinematic Stirling currently being developed under the automotive program. However, the free-piston Stirling engine inherently provides a high payoff - high risk type of advanced heat engine offering the potential for long life and high reliability, high efficiency, simplicity, low vibration and relatively low noise.

RE-1000 ENGINE CHARACTERIZATION

In order to get "hands on" experience with free-piston Stirling technology an in-house program was started at NASA Lewis. One of the first activities was the purchase, installation and test of a free-piston Stirling engine. The engine, RE-1000, was designed and built by Sunpower, Inc., of Athens, Ohio. The engine is shown schematically in Fig. 2 and its characteristics are presented in Ref. 14. The nominal 1 kW engine is an electrially heated single-cylinder research engine with dashpot load. The 30 Hz engine was designed for helium at a pressure of 70 bar.

The engine with dashpot load was tested under a joint cooperative interagency agreement between NASA and DOE/ORNL. About 800 data points were recorded in a series of sensitivity tests. The detailed data will be published in a future report. The sensitivity tests were conducted to determine the affect of the following on engine performance.

(1) regenerator porosity variation,
(2) different displacer rod area,
(3) piston mass variation, and
(4) working gas variation.

The RE-1000 engine is a research engine and as such has not been designed for maximum efficiency. Nevertheless an efficiency of 33 percent has been achieved with this engine (efficiency defined here as the output shaft power divided by the heat into the heater). Along with the engine testing, data are being used to validate a basic Stirling performance code. This work is funded also under the joint NASA/Lewis-DOE/ORNL cooperative interagency agreement. The code in its present form accurately predicts trends in performance. Predicted power and efficiency are in good agreement with test data within about ±10 percent. A typical comparison is shown in Fig. 3 where the efficiency prediction corresponds to the experimental efficiency and the power prediction over-predicts by about 6.5 percent. The predictions in Fig. 3 are in the unconstrained mode. 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. The model is currently being 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 UNIT

As part of the NASA Lewis free-piston Stirling engine program funded by DOE/ORNL, a hydraulic output device was designed and built for the RE-1000. The detail design work and the fabrication of the system was done by Foster-Miller Inc., of Waltham, Mass. As with the original design of the RE-1000, the hydraulic output device was designed to be a rugged test bed to be used as a research tool. The unit features modular design for flexibility of test configurations, ease of instrumentation, balanced or unbalanced operation, and two or four pulse/cycle pump configurations.

Thus, the RE-1000 can be used for hydraulic and gas compressor output performance investigation. A cut-away view of the engine modified for hydraulic output is shown in Fig. 4. The engine was just recently converted over to hydraulic output operation and is currently undergoing shakedown testing. The experimental data will be used to validate the computer code for hydraulic and gas compressor outputs. 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. 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. 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.

ENDURANCE TEST ENGINE

Reference 15 describes a 1000-hr endurance test including duty cycles and 250 dry start-stop cycles on an MTI free-piston Stirling linear alternator engine. This engine was then refurbished and is now running on externally pressurized gas bearings. Refurbishment included replacing displacer rod, displacer, flange and post, power piston and cylinder. These changes were incorporated to facilitate conduction of a 10 000-hr projected lifetime test to augment the results being obtained from the Space Power Demonstrator Engine (SPDE). The engine currently has accumulated over 5500 hr (after engine refurbishment) of operation without any down time attributed to space-related operation such as gas bearing failure or alternator, heater, regenerator, or cooler failures. The engine is currently operating at full stroke with an output of about 2 kWe. The frequency is 60 Hz. Helium is the working fluid at 62 bar mean pressure. The heater temperature is maintained at 973 K. The engine is shown in Fig. 5. The engine operation is almost completely automated. The targeted utilization rate has been set at 20 hr for every 24-hr day. This has been achieved from around Sept. 1984 with the exception of the holiday season.

The engine operating conditions are tabulated in Fig. 6. The funding was provided by the Gas Research Institute, the SP-100 program and Mechanical Technology Inc.

STIRLING SP-100 PROGRAM BACKGROUND

As part of the SP-100 Advanced Technology Program, NASA Lewis is conducting and managing work directed toward Stirling engine energy conversion. As shown in Fig. 7 this program is long range and broadly based; and supports the listed key technology areas needed for SP-100 application. Specifically, the Stirling cycle is the most efficient thermodynamic heat engine cycle that exists. This permits the use of smaller heat sources (e.g., solar collectors) but more importantly the ability to operate at a much lower temperature. Lower temperatures may permit the use of conventional materials such as stainless steel rather than the more expensive refractory materials. The Carnot cycle efficiency is a function of the ratio of the hot metal temperature to the cold metal temperature (ratio of temperature of heat added to heat rejected). In the Automotive Stirling Engine (ASE) program this ratio is around 3.3 yielding a Carnot cycle efficiency of around 70 percent. At this temperature ratio, the percent of Carnot cycle efficiency can be as high as 60 to 65 percent. However, for space application, where mass and volume constraints are of paramount importance, temperature ratios in the range of 2 are required in order to achieve a minimum system mass. With a temperature ratio of 2 the Carnot cycle efficiency is 50 percent. The percent of Carnot cycle efficiency that can be achieved is about 55 to 60 percent. Therefore, depending upon the temperature ratio dictated by the application, system efficiencies can range from 27.5 to 30 percent at low temperature ratios and 42 to 45.5 percent for high temperature ratio systems. Remember, the Stirling engine is a high efficiency engine.

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. The initial successful operation of the engine occurred in less than 16 mo from start of work - a significant achievement. The nominal design was 25 kWe from the two opposed - piston Stirling engine - linear alternator system. The engine is shown in Fig. 8. It is about 1-1/4 m in length and about 1/3 m in diameter. The engine 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. A general description of the engine is given in Ref. 16. Nevertheless, a few of the engine and facility features are as follows: Molten salt is used to heat the heater of the opposed piston engine. A cut-away of the engine is shown in Fig. 9. The salt facility can deliver up to 150 kW of heat to the nitrate/nitrite salt; and can circulate 50 gal/min of hot salt. The use of molten salt helped keep the heater at a more uniform temperature than a gas-fired combustor.

Because the operating frequency of the engine has been extended to 105 Hz from heretofore 60 Hz engines; and due to the high power to weight ratio desired, beryllium was chosen for the moving parts. Beryllium possesses low density, high specific strength, and high specific modulus. To illustrate the progress that has been made with beryllium parts refer to Fig. 10 which shows gas-spring pistons fabricated from beryllium. The location of the gas spring pistons are shown in Fig. 11 which is a cross section of the engine. You will note that both heater and cooler heat exchangers consist of many short tubes. This configuration presented a challenge in fabrication. A design such as this would not be used for space-rated reliability but was selected based upon the very tight demonstration schedule. Figure 12 shows a technician assembling one of the two heater heads. There are 1600 tubes in each heater and 1900 tubes in each cooler. Each tube was about 2.5 mm o.d. A gold-based braze was used in a high vacuum furnace for joining. The tubes were first plated with a thin coat of nickel prior to brazing. Figure 13 is a photo of one of the two linear alternator plungers. Note the four circumferential rings of samarium cobalt magnets. The location of the plunger relative to the engine can best be seen by referring back to Fig. 11.

Because of the tight schedule to design, fabricate, and test the engine within a 16 mo period, the maximum engine temperature for initial testing was chosen as 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).

Figure 14 highlights some of the state-of-the-art technology that has been extended in the design and fabrication of SPDE. The pressure level for conventional free-piston Stirling engines of 60 bar was increased by a factor of 2.5 to 150 bar - a level currently used for kinematic Automotive Stirling engines. The frequency was increased to 105 Hz from the usual 60 Hz engine. Both the pressure and frequency were increased to increase the engine power density. Figure 15 compares predicted to experimental results for an initial half-pressure condition.

HYDRODYNAMIC GAS BEARINGS

The SPDE engine was designed with hydrostatic gas bearings, for expediency rather than as the preferred space-power design. Hydrodynamic bearings for free-piston Stirling engines provide the potential of simplicity in design accompanied by improved efficiency as well as reducing the size and mass of the engine system 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, as an SP-100 contractor, has demonstrated a spin-lubricated hydrodynamic gas bearing concept. This was performed on a Sunpower 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 the test bed engine, the bearing clearances are less than a factor of two different.

Also, lower test pressure should be more prone to instability and thus may be a more severe test. Very similar are gas-spring lengths, gas-spring diameters, bearing span, and gas-spring gaps. The dimensionless numbers governing the design are identical. The test engine was modified in the following manner. Figure 16 shows the engine which was retrofitted with a simple impulse turbine. The turbine intercepted the cooler-port gas flow a small fraction of each cycle. A schematic of the spin bearing concept is shown in Fig. 17.

Figure 18 shows the turbine buckets attached to the displacer on the right of the photograph. All three components comprise the displacer. The displacer dome is shown on the left and the puck shown in the center fits over the displacer rod.

The displacer is the only piston to be evaluated for a spin bearing at this time. Instrumentation has been installed to measure the bearing gaps and to observe any whirl or cocking. Additional instrumentation records axial displacer position, frequency, and displacer angular velocity. The test engine can be driven at 60 Hz by connecting line power to the alternator or can be operated as an engine. For the proof-of-concept test the engine was driven by putting power into the alternator. The displacer lifted off and remained stable and centered. The displacer spun at about 25 Hz.

The test rig acts as a refrigerator when motored. Thus, the cold temperature becomes a problem in terms of available test time before the instrument stability is affected. A heater is being fabricated to limit the range of these temperature variations. The engine test stand is such as to accommodate operation of the engine axis at any angle to the gravity field thereby enabling the affect of the gravity field on the bearing load to be measured.

DYNAMIC BALANCE

The SPDE engine is inherently dynamically balanced and has been discussed earlier in this report. Single cylinder free-piston engines are not inherently balanced and the balancing must be addressed.

An experiment was also devised to assess passive dynamic balancing on a single-cylinder Stirling engine. The engine used for the test is the RE-1000 engine at NASA Lewis. This 1 kW, single-cylinder, 30 Hz engine was previously discussed in this report. The engine characteristics are described in Ref. 14. The engine with a passive dynamic absorber (mounted on top of the engine casing) is shown in Fig. 19. The dynamic absorber resulted in a reduction in housing amplitude by a factor of about 30, to about 12.5 μm. Analytical predictions agreed well with experimental data as shown in Fig. 20. There is a weight penalty associated with dynamic balancing of single-cylinder engines. Passive systems require additional mass equal to about 10 percent of the engine/alternator mass; active dynamic balancing systems require only about 3 percent additional mass. Passive dynamic absorbers have fixed spring rates and cannot be tuned during operation. This type of operation has a fixed natural frequency and in turn requires a design band width equal to the full range of possible engine operating frequencies. On the other hand with an active dynamic absorber the required operating band width due to engine frequency is immaterial since the unit can drive its natural frequency to a point very close to the operating frequency of the engine. Calculations performed by system contractors in support of the SP-100 program indicated that casing amplitudes of less than 75 μm should not pose a problem to the payload.

CONCLUDING REMARKS

A 2 kW free-piston Stirling endurance engine has been run by MTI for over 5500 hr. No failures of space-related components have been detected. Even though externally-pumped hydrostatic gas bearing have been used, instead of internally pumped bearings, the engine and bearings ran well.

Dynamic balancing has been achieved on a single-cylinder free-piston Stirling engine incorporating a passive dynamic absorber. The vibration amplitude on the 1 kW, 30 Hz engine has been reduced by a factor greater than 30 to a level acceptable to spacecraft payloads.

A 25 kW SPDE engine has been designed, fabricated, installed, and tested at reduced pressure levels. Performance codes predicted 6.7 kWe under conditions at which the engine-alternator generated 6.5 kWe. The engine was tested at 75 bar pressure and 73 Hz. 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 below 8 kg/kW. Power per piston has been scaled up by a factor of 4 in the SPDE design. 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.

Hydrostatic gas bearings have been demonstrated on the endurance engine as well as on the current SPDE engine. The hydrodynamic spin-lubricated (impulse turbine) gas bearing concept has been successfully demonstrated on the displacer of an operating engine. Using the RE-1000 code predictions, we can calculate power and efficiency within ±10 percent. In conclusion, we feel that free-piston Stirling engines are just starting to achieve the attention and credibility that they deserve for space-power application. 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.

Other features include the use of gas bearings (potential for life and reliability), and the use of beryllium which has been previously discussed. Further technology extensions include scale up in total power by a factor of eight. Currently the engine has not been subjected to the full power design point pending completion of the low pressure evaluation. This is the first designed-for-space Stirling engine that has been built and run at a temperature ratio of 2. Consequently, we look forward to operating the engine at design conditions of 25 kWe.

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- GENERIC FPSE TECHNOLOGY FOR SPACE POWER AND TERRESTRIAL HEAT PUMP APPLICATION
  --IAA (DOE/ORNL-LeRC)
    - RE-1000 ENGINE
    - CODE VALIDATION
    - HYDRAULIC OUTPUT
    - 1000 HOUR ENDURANCE TEST
- SP-100 SPACE POWER PROGRAM
    - 10 000 HOUR ENDURANCE TEST CONTINUATION
    - DESIGN OF 25 KWe FPSE; TEMPERATURE RATIO 2.0
    - TEST SPIN-LUBRICATED HYDRODYNAMIC GAS BEARING
    - DESIGN, FAB, TEST 25 KWe, SPDE AT 650 K

Figure 1. - Lewis free-piston Stirling activities.

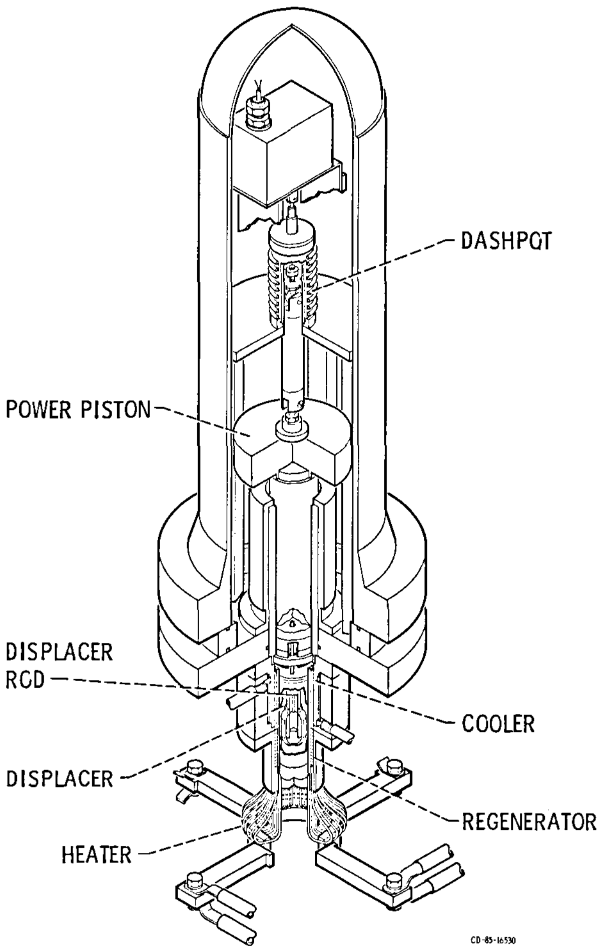

Figure 2. - RE-1000 free-piston Stirling with dashpot load.

	FREQUENCY HZ	BRAKE EFFICIENCY	OUTPUT POWER WATTS	PHASE ANGLES DEGREES
EXPERIMENTAL	30.4	29	983	50.8
PREDICATED (UNCONSTRAINED)	29.9	29	1047	52.1

Figure 3. - RE-1000 engine performance - predicted versus experimental.

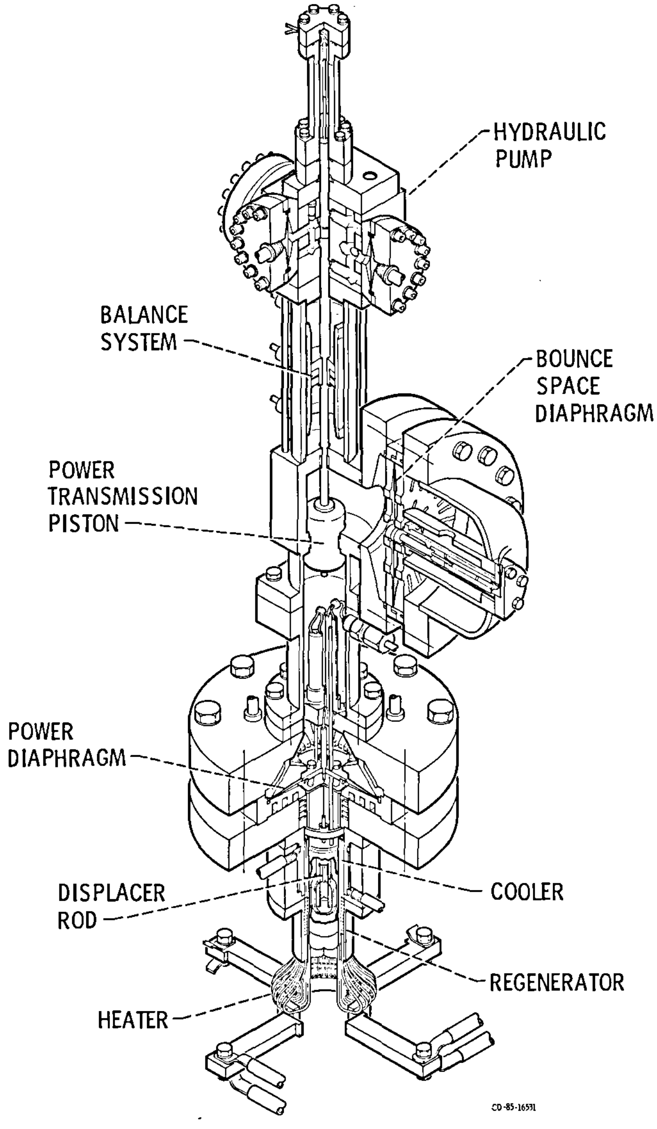

Figure 4. - RE-1000 free-piston Stirling with hydraulic output.

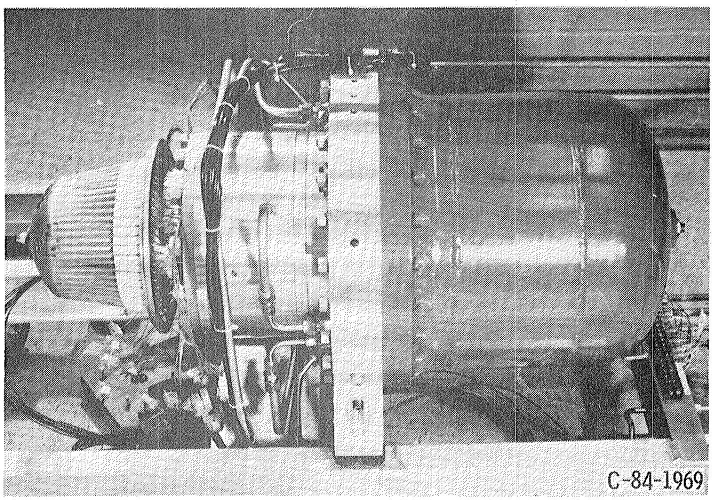

Figure 5. - Free-piston Stirling / linear alternator endurance engine at Mechanical Technology Inc.

● 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	--	EXTERNALLY PUMPED HYDROSTATIC

Figure 6. - 10 000 Hour endurance test conditions using existing 2 kW MTI engineering model engine.

- IS A LONG RANGE BROADLY BASED PROGRAM
- SUPPORTS KEY TECHNOLOGY AREAS NEEDED FOR:
  - HIGH EFFICIENCY
  - GROWTH
  - LIGHT WEIGHT
  - MEETS REQUIREMENTS AT LOWER TEMPERATURES
  - INCREASED RELIABILITY AND LIFETIME

Figure 7. - NASA SP-100 advanced technology program.

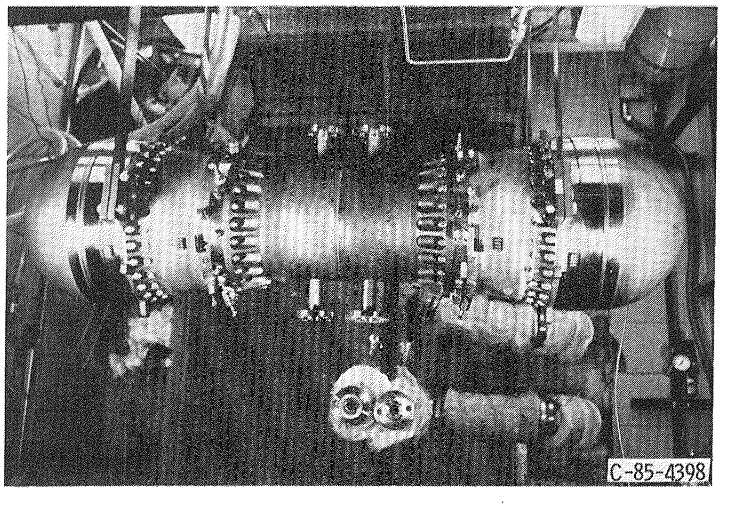

Figure 8. - 25 kWe Space Power Demonstrator Engine(SPDE) at Mechanical Technology Inc.

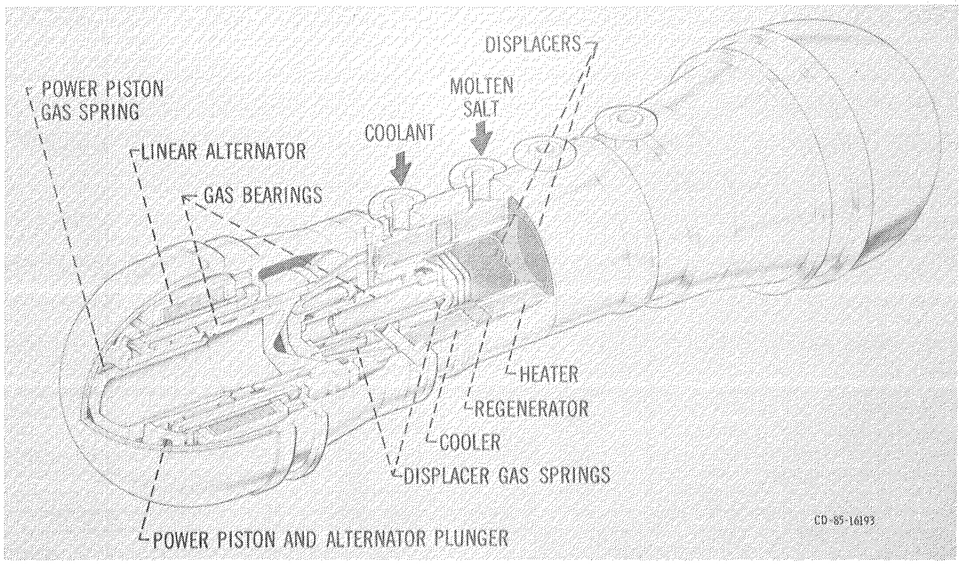

Figure 9. - Space power demonstrator engine.

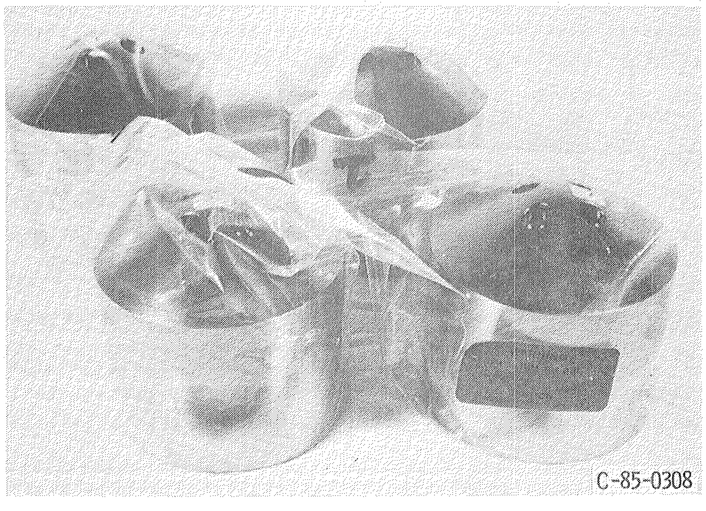

Figure 10. - SPDE beryllium gas spring pistons.

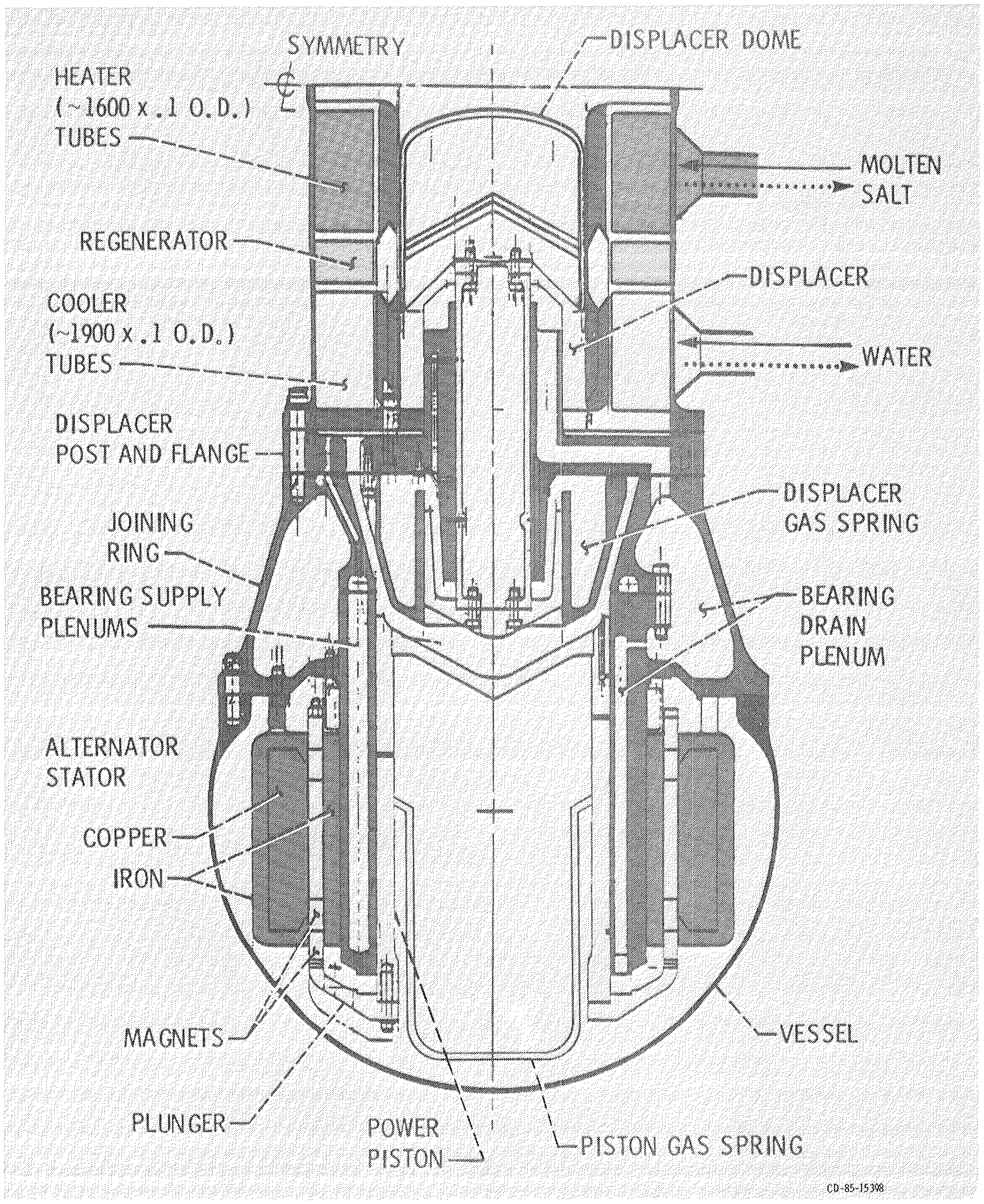

Figure 11. - 25 kWe SPDE.

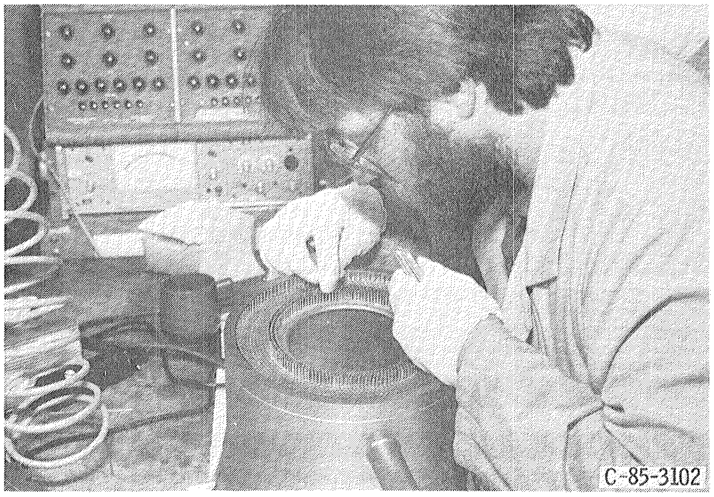

Figure 12. - Assembly of SPDE molten salt heat exchanger.

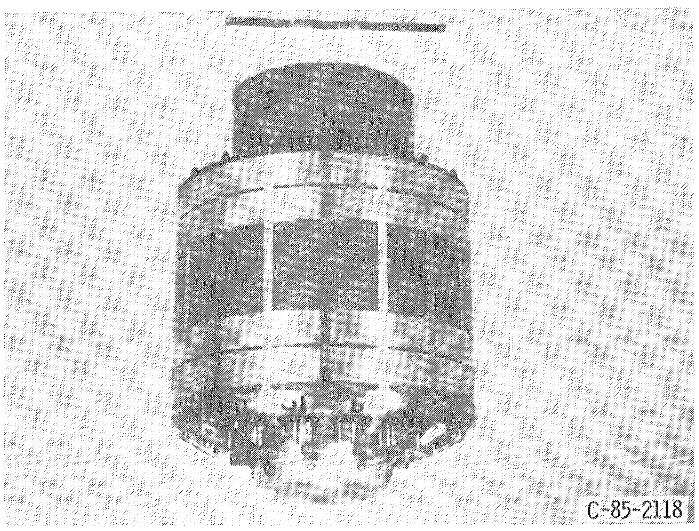

Figure 13. - SPDE alternator plunger assembly.

- PRESSURE-UP FACTOR OF 2.5
- FREQUENCY-UP FACTOR OF 1.75
- PISTON AREA-UP FACTOR OF 1.6
- TEMPERATURE RATIO-DOWN FACTOR OF 1.5
- BERYLLIUM COATED COMPONENTS
- GAS BEARINGS
- DYNAMICALLY BALANCED
- PISTON POWER SCALE UP-FACTOR OF 4
- ENGINE POWER SCALE UP-FACTOR OF 8
- MOLTEN SALT HEAT INPUT
- 14 000 BRAZE JOINTS

Figure 14. - Free-piston State-Of-The-Art SPDE technology extension.

	PREDICTED	EXPERIMENTAL
ELECTRIC POWER OUT, kWe	6.7	6.5
FREQUENCY, HERTZ	71	73
T_h/T_c	2.0	2.0
PRESSURE, BAR	75	75

Figure 15. - Initial SPDE test result at half pressure (75 BAR) design conditions.

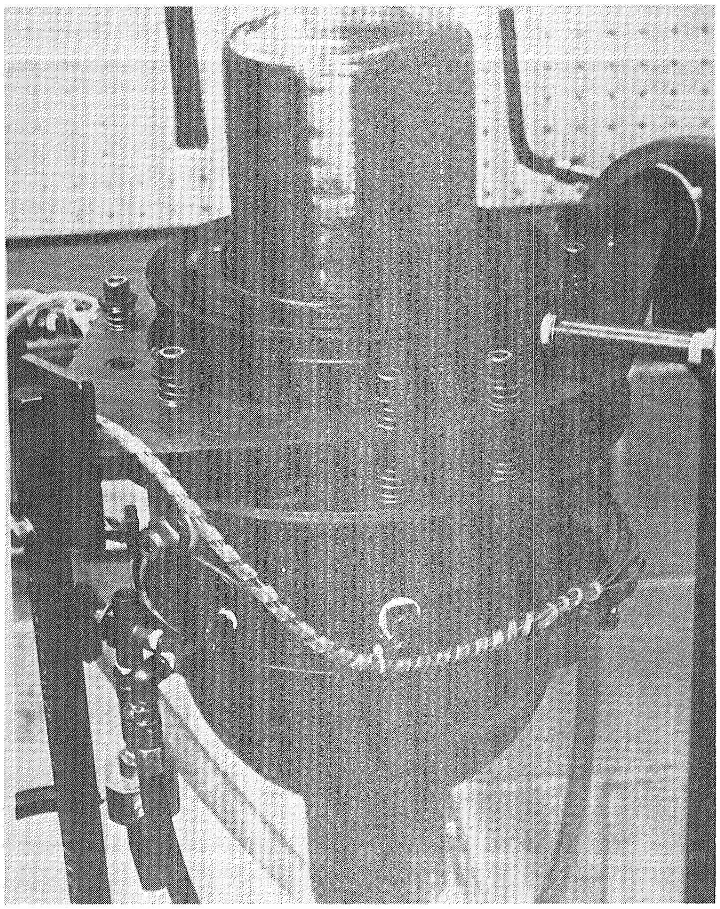

Figure 16. - Sunpower Inc. 1 kW Stirling engine used for hydrodynamic spin-bearing concept evaluation.

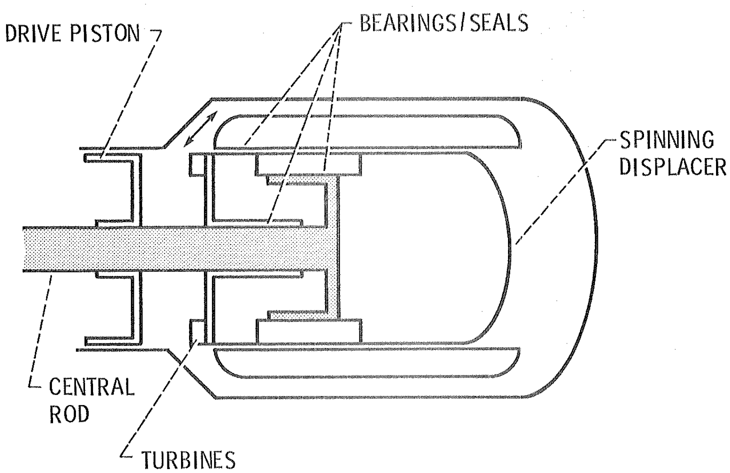

Figure 17. - Spin bearing test rig schematic.

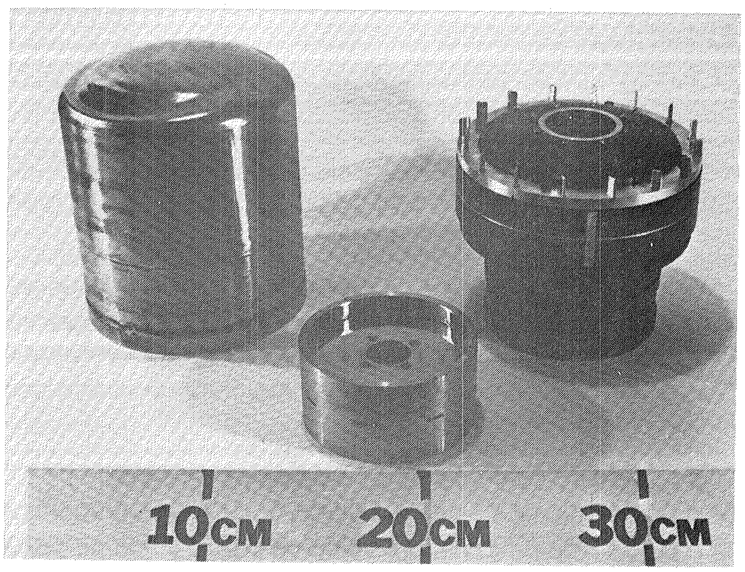

Figure 18. - Spin-bearing displacer components on 1 kW Stirling engine.

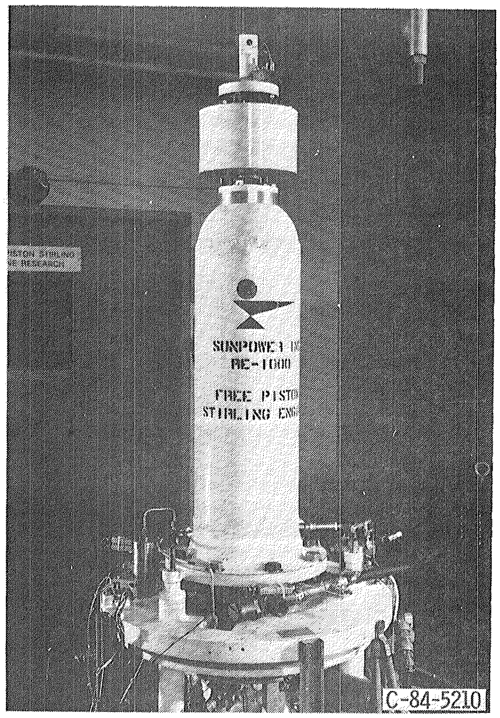

Figure 19. - 1 kW RE-1000 free-piston Stirling engine with dynamic absorber balancing unit.

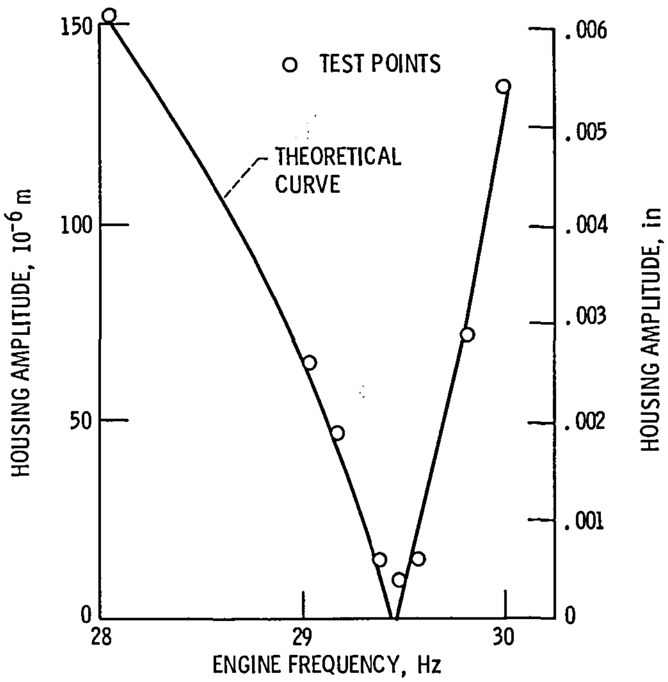

Figure 20. - Housing amplitude compared to theoretical value on RE-1000 free-piston Stirling engine.

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16. Abstract
An overview of the National Aeronautics and Space Administration (NASA) Lewis Research Center (Lewis) free-piston Stirling engine activities is presented. These activities include; (1) a generic free-piston Stirling technology project being conducted to develop technologies synergistic 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 demonstration project as part of the SP-100 program being conducted in support of the Department of Defense (DOD), DOE, and NASA/Lewis. The generic technology effort includes extensive parametric testing of a 1 kW free-piston Stirling engine (RE-1000), development and validation of a free-piston Stirling performance computer code, and fabrication and initial testing of an hydraulic output modification for the RE-1000 engine. The space power technology effort, under SP-100, addresses the status of the 25 kWe Space Power Demonstrator Engine (SPDE) including early test results.

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

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