NASA TM-87028

NASA-TM-87028
19850019457

DOE/NASA/1005-5
NASA TM-87028

Overview of the 1985 NASA Lewis Research Center SP-100 Free-Piston Stirling Engine Activities

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
Twentieth Intersociety Energy Conversion Engineering Conference
cosponsored by the ANS, ASME, SAE, IEEE, AIAA, ACS, and AIChE
Miami Beach, Florida, August 18–23, 1985

Printed in the United States of America

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

---

[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.

DOE/NASA/1005-5
NASA TM-87028

Overview of the 1985 NASA Lewis Research Center SP-100 Free-Piston Stirling Engine Activities

Jack G. Slaby
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Work performed for
U.S. DEPARTMENT OF ENERGY
Conservation and Renewable Energy
Division of Building and Community Systems
Washington, D.C. 20545
Under Interagency Agreement DE-AI05-820R1005

Prepared for
Twentieth Intersociety Energy Conversion Engineering Conference
cosponsored by the ANS, ASME, SAE, IEEE, AIAA, ACS, and AIChE
Miami Beach, Florida, August 18–23, 1985

OVERVIEW OF THE 1985 NASA LEWIS RESEARCH CENTER SP-100 FREE-PISTON STIRLING ENGINE ACTIVITIES

Jack G. Slaby
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-2584-1

SUMMARY

An overview of the 1985 (NASA) Lewis Research Center free-piston Stirling engine activities in support of the SP-100 Program is presented. The SP-100 program is being conducted in support of the Department of Advanced Research Projects Agency (DARPA) and the Department of Energy (DOE), and NASA. This effort is keyed on the design, fabrication, assembly, and testing of a 25 kW_e Stirling space-power technology-feasibility demonstrator engine. Another facet of the SP-100 project covers the status of a 9000-hr goal endurance test conducted on a 2 kW_e free-piston Stirling/linear alternator system employing hydrostatic gas bearings. Dynamic balancing of the RE-1000 engine (a 1 kW_e free-piston Stirling engine) using a passive dynamic absorber will be discussed along with the results of a parametric study showing the relationships of Stirling power converter specific weight and efficiency as functions of Stirling engine heater to cooler temperature ratio. Planned tests will be described covering a hydrodynamic gas bearing concept for potential SP-100 application.

INTRODUCTION

The evolution of and the background for the free-piston Stirling engine was covered in reference 1 along with some of its potential advantages for both terrestrial and space application. The work described in this paper is primarily keyed on free-piston Stirling work performed or managed by personnel at the NASA Lewis Research Center, in support of the SP-100 Program.

The SP-100 Program was established through a 1983 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. This report will focus on the free-piston application of the Stirling engine. In addition to the SP-100 work, NASA Lewis is conducting free-piston stirling technology research generic to both space power and terrestrial heat pump applications under a cooperative, cost-shared Interagency agreement with the Department of Energy (DOE)/Oak Ridge National Laboratory (ORNL). This generic technology effort includes extensive parametric testing of a 1 kW free-piston Stirling engine; development and validation of a free-piston Stirling performance code; and installation and shake-down testing of an hydraulic output modification to a 1 kW free-piston Stirling engine. This generic technology effort will not be further addressed 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.

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 the 1983 Eighteenth Intersociety Energy Conversion Engineering Conference (IECEC) reference 2 provided an overview of the DOE/NASA ASE program. References 3 to 12 list a series of reports which summarize both NASA directed and NASA conducted kinematic Stirling work.

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 9 to 11 yr and total expenditures have been on the order of 15 million dollars - a very modest amount for new engine development. Even at this low total level, the technology is advancing rapidly.

SP-100 STIRLING PROGRAM OBJECTIVE

As part of the phase I SP-100 program, three system concepts are being considered for SP-100 missions. The three concepts are thermionic, thermoelectric and Stirling. In order to make a meaningful selection, various feasibility issues of each concept must be resolved. This report keys on the Stirling technology issues being addressed by the Lewis Research Center. Before discussing this work, first consider the SP-100 development ground rules shown in figure 1. The system power range shall be in the 100 kW to 1 MW range (although the baseline concept currently stands at 100 kW_e). The 7 yr life requires 7 yr of actual power generation over a 10 yr operational period. The stowed system length at launch must be equal to or less than one-third of the shuttle bay length.

The advantage of the Stirling system concept over the other two systems is the high system conversion efficiency (greater than 20 percent compared to less than 10 percent for either competing system) obtainable at relatively low heat source temperatures. This permits the use of a smaller reactor but more importantly the ability to operate the reactor at a much lower temperature. For example, the Stirling fuel clad temperatures are 300 to 500 K cooler than the thermoelectric system and 600 to 800 K cooler than the thermionic system.

Lower reactor temperatures may permit the use of conventional materials such as stainless steel rather than the more expensive refractory materials. Because free-piston Stirling technology is in the early stages of development several key issues relative to performance and lifetime need be considered. These issues are listed in figure 2. They include scalability, performance in terms of percentage of Carnot cycle efficiency - at temperature ratios around 2, engine specific mass, dynamic balance of the power conversion unit, and lifetime. The temperature ratio is defined in this report as hot exterior metal temperature of the heater (T_h), divided by the cold exterior metal temperature of the cooler (T_c). In the Automotive Stirling Engine (ASE) program, as an example, an indicated cycle efficiency in excess of 70 percent of Carnot cycle efficiency is currently being achieved. The temperature ratio in the ASE program is 3.3. However, for the 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. A preliminary plot is shown in figure 3 demonstrating the temperature ratio influence on the percent of Carnot cycle efficiency and specific mass of the Stirling engine. The engine efficiency and specific mass then affect the total system mass (radiator included).

Although the calculations are preliminary at this time, figure 4 illustrates an approximate mass breakdown for a 100 kW_e stainless steel system. The reactor outlet temperature is 1000 K and the total system mass is 3100 kg.

THE SPACE POWER DEMONSTRATOR ENGINE (SPDE)

The SPDE engine, designed, fabricated and under test at Mechanical Technology Incorporated (MTI) in Latham, NY will attempt to demonstrate experimentally the feasibility issues listed in figure 2 with the exception of lifetime. Lifetime is discussed separately and tests are being conducted on another engine operated at MTI. The objective of the SPDE design is to demonstrate in less than 17 mo the key issues, with actual hardware, that will contribute toward SP-100 concept selection.

At the time of this report all components have been ordered and a targeted shake-down test period is scheduled to start around the end of May. A few of the engine and facility design features are as follows: Figure 5 shows a molten salt facility that will be used to heat the heater head of the opposed piston engine. The salt facility can deliver up to 150 kW of heat to the nitrate/nitrite salt. The skid-mounted system can circulate up to 50 gal/min of hot salt. Reference 13 presents a description of the SPDE engine.

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 figure 6 which shows gas-spring pistons fabricated from beryllium. The location of the gas spring pistons are shown in figure 7 which is a cross section of the engine and figure 8 is an artist's conception of the 25 kW opposed-piston engine module. 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 17-mo demonstration schedule. Figure 9 shows a typical cooler plate with approximately 1900 holes per plate - each hole being about 0.1 in od (2.5 mm). The gold-based braze was conducted in a high vacuum furnace. The tubes were plated with a thin coat of nickel. Figure 10 shows a completed cooler assembly after brazing and integrity checking. Figure 11 shows a completed outer stator cage of one of the SPDE linear alternators.

ENDURANCE TEST ENGINE

Reference 14 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 9000-hr projected lifetime test to augment the feasibility issues being evaluated on the SPDE engine. The engine currently has accumulated over 4500 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 kW_e. 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 figure 12. 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 September 1984 with the exception of the holiday season.

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: (1) 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; (2) 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 (3) seal losses in both systems can be about equal.

The hydrodynamic gas bearing concept is in the early stages of being demonstrated under contract with Sunpower Inc., at Athens, Ohio. A Sunpower 1 kW free-piston Stirling engine as shown in figure 13 will be 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 space engines. Figure 14 shows some preliminary values of the pertinent parameters between the Sunpower test engine and the SPDE space-size engine. For example, even though the pressure in the space demonstrator 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 engine test stand is such as to accommodate operation of the engine axis at any angle to the gravity field thereby enabling the effect of the gravity field on the bearing load to be measured. The test engine may be driven at 60 Hz by connecting line power to the alternator or can be operated as an engine. A simple impulse turbine is mounted on the displacer and intercepting the cooler port gas flow a small fraction of each cycle. A schematic of the spin bearing test engine is shown in figure 15. The displacer is the only piston to be evaluated for a spin bearing at this time. Instrumentation will measure the bearing gaps, to observe any whirl or cocking. Additional instrumentation will measure axial displacer position, and frequency and displacer angular velocity. The objective of this demonstration is to identify regions of satisfactory stable operation and to obtain satisfactory design characteristics.

DYNAMIC BALANCE

Another Stirling technology feasibility issue is that of dynamic balance. An opposed-piston engine such as the SPDE is inherently dynamically balanced. MTI has tested a nominal 3 kW opposed piston engine operating at 60 Hz and measured a casing amplitude of about 3 mils (75 μm). Calculations performed by the systems contractors indicate that this magnitude should not pose a problem to the payload. 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 the Lewis Research Center. This 1 kW, single-cylinder, 30 Hz engine was manufactured by Sunpower Inc., of Athens, Ohio. The engine characteristics are described in reference 15. The engine with a passive dynamic absorber (mounted on top of the engine casing) is shown in figure 16. The dynamic absorber resulted in a reduction in housing amplitude by a factor of about 30, to about 1/2 mil (12.5 μm). Analytical predictions agreed well with experimental data as shown in figure 17. 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.

Sunpower, as an SP-100 contractor, has conducted analytical support and carried out parametric studies to assess 25 kW_e space-power design concepts. One of the interesting comparisons was an analysis showing the relative engine performance between an opposed piston engine (SPDE type design) and a single-cylinder engine with dynamic balancing. The comparison was made at the same output power of 25 kW_e, a temperature ratio of 2, and linear alternator output.

The normalized results are summarized in the tabulation.

	SPDE	Single cylinder	
	Opposed piston	Passive balance	Active balance
Specific weight	1.0	1.08	1.0
Indicated efficiency	1.05	1.0	1.0

Based on the accuracy of the assumptions and calculations one can conclude that the specific weight and performance (indicated efficiency) are about equal for either concept - assuming that the single cylinder concept incorporates the active balancing system.

PARAMETRIC INVESTIGATION

The design of Stirling engines for space application is far different from previous Stirling engine design considerations for terrestrial uses such as heat pumps or automotive applications. Space systems will either be powered by nuclear reactors (with associated shielding) or solar collectors and receivers with radiators to reject heat. Thus, the weight of the overall system must be minimized, which dictates that the radiator temperature be relatively high. For terrestrial application the temperature ratio is around 3.0. Space application requires temperature ratios around 2.0. This is an area in which heretofore very little hardware has been needed or built. Consequently Sunpower Inc., under NASA Lewis contract used their scaling code and experience to investigate how the percent Carnot cycle efficiency and specific weight were affected by the engine temperature ratio. Then by cross-plotting they obtained the relation between specific weight and percent of Carnot cycle efficiency for different temperature ratios.

The intent of this report is not to delve into the details which will be presented at a later date in a NASA contractor report, but to present the preliminary results of percent Carnot cycle efficiency as a function of engine specific weight for - in the case shown in figure 18 - a temperature ratio of 2.0. Also shown in the figure is the growth potential expected based upon a better understanding of the various loss mechanisms. Some of these loss mechanisms are not fully understood and are noted below: (1) nonuniform gas flow in the manifolds from the working space to the heater-regenerator-cooler assembly; (2) "increased" gas thermal conductivity occurring in the regenerator. This unique loss mechanism increases the quantity of energy lost between the heater and cooler due to a thermal short circuit through the regenerator gas. This particular loss mechanism is aggravated by the use of high frequencies which requires large regenerator cross-sectional flow areas and short regenerator lengths to minimize flow losses. This configuration does not prevail in current terrestrial Stirling engines but was utilized for the current space-power type module. The impact of this loss can be significant depending on the specific coefficients used in the correlation model. The operation of the SPDE will provide much needed information to better understand this mechanism; (3) other conventional losses which are moderately well-understood include gas spring losses, heat transfer and pressure drop in cyclic flow, leakage losses involving centering ports, and flow maldistribution losses.

Keep in mind that the predictions of figure 18 are for a conventional free-piston/linear alternator system using helium working fluid. The improvement potential is based upon a better understanding of all loss mechanisms, an improved definition of the specific mass versus efficiency tradeoff, and refined structural concepts and material selections. The growth potential is conservative in that nonconventional engine arrangements have not been factored into the projections. Also a secondary gas was not considered for reduction of gas spring losses. Finally, the use of hydrogen working fluid may offer potential benefits that were not included in these growth projections.

The results of this brief discussion represent a realistic assessment of current and growth potential of specific mass and percent of Carnot cycle efficiency of a FPLA concept directed toward space-power missions.

CONCLUDING REMARKS

A year ago the free-piston Stirling SP-100 effort was just getting underway. Since that time a 25 kW_e SPDE engine has been designed, metal has been cut, heaters and coolers brazed, a salt facility for heating the engine has been installed and engine assembly has started. This engine at MTI has been designed for low specific-mass, 8 kg/kW, with design and material substitution to achieve 6 kg/kW. The operating pressure is 150 bar and the frequency is 105 Hz. Nonconventional materials such as beryllium and gold brazes have been used.

An endurance engine also at MTI has been run more than 4500 hr demonstrating that gas bearings and free-piston Stirling engines are quite compatible. No failures of space-related components have been detected to date.

Dynamic balancing by Sunpower has been achieved on a single-cylinder free-piston Stirling engine incorporating a passive dynamic absorber. The vibration amplitude has been reduced by a factor greater than 30 to a level acceptable to spacecraft payloads. In addition, under another program, a FPLA design similar to the SPDE in that it consists of opposed pistons, has demonstrated inherent balance in operation and has resulted in only a 3 mil (75 μm) casing amplitude.

Hydrodynamic gas bearings have been incorporated on not just test devices but on an actual working engine by Sunpower. The hydrodynamic bearing will be incorporated into a 25 kW single-cylinder engine design. This engine design will also incorporate an active dynamic balancing system. Parametric investigations by Sunpower have shown that relationships between specific mass and percent of Carnot cycle efficiency can be established with a certain amount of confidence; and that with continued Stirling technology investigations these relations can achieve significant growth. We feel that free-piston Stirling engines are just starting to achieve the attention and credibility that they deserve for the dynamic space-power application. Stirling systems can easily be used with both nuclear and solar powered systems. At next year's meeting we hope to be able to present some of the test results emanating from the Lewis-managed SP-100 Stirling activities as well as other generic free-piston Stirling work at the Lewis.

REFERENCES

1. J.G. Slaby, "Overview of NASA Lewis Research Center Free-Piston Stirling Engine Activities," DOE/NASA/1005-2, NASA TM-83649 (1984).
2. D.G. Beremand, "DOE/NASA Automotive Stirling Engine Project Overview '83'," DOE/NASA/51040-48, NASA TM-83405 (1983).
3. "Automotive Stirling Reference Engine Design Report," MTI 81ASE164DR2, Mechanical Technology, Inc., (DOE/NASA/0032-12, NASA CR-165381) (1981).
4. "Automotive Stirling Engine Mod I Design Review Report," MTI 81ASE142DR1, Mechanical Technology, Inc., (DOE/NASA/0032-16, NASA CR-167935) (1982).
5. "Automotive Stirling Engine Development Program," MTI 83ASE334SA4, Mechanical Technology, Inc., (DOE/NASA/0032-21, NASA CR-168205) (1983).
6. W.P. Teagan, D.R. Cunningham, "Stirling Engine Application Study," DOE/NASA/0254-1, NASA CR-168087 (1983).
7. M.A. White, "Conceptual Design and Cost Analysis of Hydraulic Output Unit for 15 kW Free-piston Stirling Engine," DOE/NASA/0212-1, NASA CR-165543 (1982).
8. S. Holgersson, W.H. Percival, in Proceedings of the Twentieth Automotive Technology Development Contractors' Coordination Meeting, p. 7, SAE, Warrendale, Pa. (1983).
9. J.G. Slaby, "Overview of a Stirling Engine Test Project," DOE/NASA/1040-80/12, NASA TM-81442 (1980).
10. G.G. Kelm, J.E. Cairelli, R.J. Walter, "Test Results and Facility Description For a 40-kW Stirling Engine," DOE/NASA/51040-27, NASA TM-82620 (1981).
11. 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).
12. R.J. Miejer, B. Ziph, "Evaluation of the Potential of the Stirling Engine for Heavy Duty Application," NASA CR-165473 (1981).
13. G. Dochat, "Free-Piston Stirling Engines For Space Power," Twenty-second Automotive Technology Development Contractors Coordination Meeting, Dearborn, MI (1984).
14. G. Dochat, J. Rauch, G. Antonelli, "Free-Piston Stirling Engine Endurance Test Program," Twenty-first Automotive Technology Development Contractors Coordination Meeting, Dearborn, MI (1983).
15. J. Schreiber, "Testing and Performance Characteristics of a 1-kW Free-Piston Stirling Engine," NASA TM-82999 (1983).

- > 30 w/kg (AT 100 kWe)
- > 7 yr FULL POWER LIFE
- < 1/3 SHUTTLE CARGO BAY LENGTH (AT 100 kWe)
- POWER RANGE 50 kWe TO 1000 kWe (WITHIN ONE SHUTTLE)

Figure 1. - SP-100 development performance goals.

MAJOR ISSUES BEING ADDRESSED

- SCALABILITY - 25 kWe
- PERFORMANCE AT $T_R = 2.0$
- SPECIFIC WEIGHT = 6 kg/kWe
- DYNAMIC BALANCE
- LIFETIME - 7 YEARS

Figure 2. - Stirling engine technology feasibility issues.

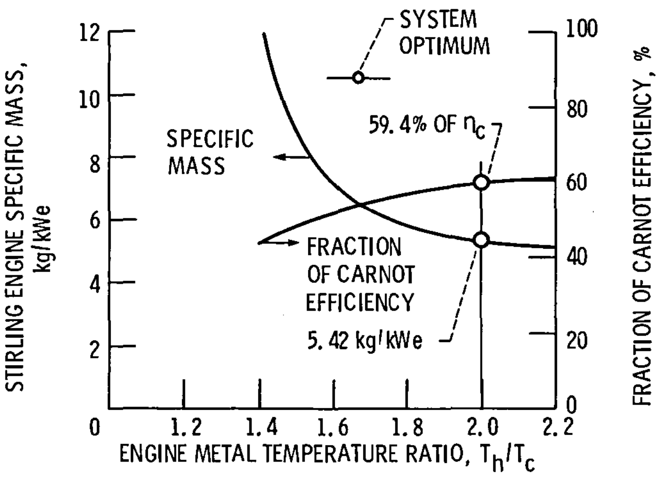

Figure 3. - Projected performance of Stirling engines.

SUBSYSTEM	PERCENT
REACTOR	13.6
SHIELD	13.8
PRIMARY HEAT TRANSPORT	5.5
STIRLING	24.1
SECONDARY HEAT TRANSPORT	4.0
RADIATOR	14.2
POWER PROCESS AND ELECTRONICS	12.7
BOOM AND DEPLOYMENT	4.1
RADIATOR RELEASE MECHANISM	0.5
STRUCTURE	7.5
	100%

Figure 4. - 100 kWe stainless steel Stirling system mass breakdown. 3100 kg total system weight, 1000 °K reactor outlet temperature.