

NASA Technical Memorandum 89832

# 1987 Overview of Free-Piston Stirling Technology for Space Power Application

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FREE-PISTON STIRLING TECHNOLOGY FOR SPACE  
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The NASA logo, consisting of the word "NASA" in a bold, sans-serif font.

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### ABSTRACT

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An overview is presented of the National Aeronautics and Space Administration (NASA) Lewis Research Center free-piston Stirling engine activities directed toward space-power application. Free-piston Stirling technology is applicable for both solar and nuclear powered systems. As such, NASA Lewis serves as the project office to manage the newly initiated NASA SP-100 Advanced Technology Program. This 5-yr program provides the technology thrust for providing significant component and subsystem options for increased efficiency, reliability and survivability, and power output growth at reduced specific mass.

One of the major elements of the program is the development of advanced power conversion concepts of which the Stirling cycle is a viable growth candidate. Under this program the status of the 25 kWe opposed-piston Space Power Demonstrator Engine (SPDE) is presented. Included in the SPDE discussion are comparisons between predicted and experimental engine performance, enhanced performance resulting from regenerator modification, increased operating stroke brought about by isolating the gas bearing flow between the displacer and power piston, identifying excessive energy losses and recommending corrective action, and a better understanding of linear alternator design and operation.

Technology work is also conducted on heat exchanger concepts, both design and fabrication, to minimize the number of joints as well as to enhance performance. Design parameters and conceptual design features are also presented for a 25 kWe, single-cylinder free-piston Stirling space-power converter. A cursory comparison is presented showing the mass benefits that a Stirling system has over a Brayton system for the same peak temperature and output power.

### INTRODUCTION

Under a 1985 memorandum of agreement between the Strategic Defense Initiative Organization (DOD), the Office of Aeronautics and Space Technology (NASA/OAST), the SP-100 Program has started Phase II - a 5-yr effort to design, develop, and demonstrate at ground test sites, the operation of the major subsystems of a 300 kWe nuclear/thermoelectric power system. The four functional elements of the SP-100 Phase II Program are: (1) SP-100 Ground Engineering Systems Development, (2) NASA SP-100 Advanced Technology, (3) NASA SP-100 Civil Missions Analysis and Requirements Definition, and (4) SP-100 Military Missions Analysis and Requirements Definition.

NASA/OAST is responsible for the SP-100 Advanced Technology Program - of which the free-piston Stirling advanced technology is an important segment. The NASA SP-100 Advanced Technology Program is intended to augment the Ground

Engineering System (GES) engineering development and ground testing of major subsystems being conducted by the Department of Energy (DOE) and is structured to enhance the chances of success for the overall SP-100 nuclear power system development. The Program is focused on providing significant component and subsystem options for increased efficiency, survivability, growth at reduced weights, and higher reliabilities. These goals will be attained through the conduct of the broad based research and technology program which includes the following elements: Space Missions Support; Systems Analysis to guide the research and technology efforts and to identify the pay-offs; Advanced Conversion Technology Development; Thermal Management; Advanced Power Conditioning and Control; Space Power Materials and Structures; and, Spacecraft Environmental Effects.

This paper keys on the advanced conversion technology and, more specifically, the free-piston Stirling advanced technology. The Stirling development is a long range broadly based program and will expand the technology developed during Phase I (as shown in Fig. 1) and will proceed with the development of technology leading to a space-qualified, high temperature, high efficiency, lightweight Stirling engine of the configuration necessary to meet SP-100 mission requirements. The major milestones of this program are listed in Fig. 2.

The work described in this report is either conducted at or managed by NASA Lewis. The two significant contractors are Mechanical Technology, Inc. of Latham, NY and Sunpower Inc. of Athens, Ohio.

### WHY FREE-PISTON STIRLING FOR SPACE POWER?

The Stirling free-piston system has many attractive attributes, several of which are tabulated in Fig. 3. Specifically, the Stirling cycle is the most efficient thermodynamic heat engine cycle that exists. Of the concepts considered for SP-100 selection, the Stirling cycle has the highest efficiency for the same given heat input and heat rejection temperatures. Because the Stirling system employs the gas bearing - either hydrodynamic or hydrostatic - there is the potential for long life and high reliability.

A system composed of a Stirling engine/linear alternator has only two moving parts per cylinder - that is the displacer and the power piston/alternator plunger. The result is a relatively simple configuration. A single-cylinder engine can be balanced either actively or passively using a springmass combination. Stirling engine energy converters are compatible with either nuclear or solar energy input.

Free-piston Stirling engines contain no sliding rod seals such as those present in the kinematic

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

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

#### STIRLING/BRAYTON SYSTEM MASS COMPARISONS

Reference 1 has conducted studies to generate system mass sensitivities. For the purpose of this discussion, comparisons are made between solar dynamic Brayton and Stirling systems at the 35 kWe power level. Each system was optimized for minimum system mass at three different temperature levels. For the Stirling, the temperature corresponds to the heater head temperature and for the Brayton the turbine inlet temperature (TIT). Figure 4 shows the variation of Brayton system mass with cycle temperature ratio (regenerator effectiveness of 0.95). Each point on the three curves represents a local minimum system mass obtained by systematically converging on a cycle pressure ratio which yielded the lowest system mass for the particular temperature ratio. For each curve, as the temperature ratio is increased, system mass first decreases due to increased system efficiency and after passing through a minimum, increases due to the increasing radiator mass. Note that with increasing TIT the mass versus temperature ratio (i.e., system efficiency) tradeoff curves become flatter. This occurs because the minimum mass points are obtained at increasingly higher efficiencies and also at increasingly higher mean heat rejection temperatures. Hence, a given deviation from the minimum mass temperature ratio will result in a smaller mass change at the higher TIT. Brayton system efficiencies represented in this figure varied from 23.5 to 36 percent as the temperature ratio increased from 2.8 to 4.2. System mass models were generated from State-of-Art (SOA) technology dating back to the 1960's, except for the assumed concentrator specific mass of  $1.22 \text{ kg/m}^2$ . A radiator specific mass of  $5 \text{ kg/m}^2$  was assumed as was an emissivity of 0.88.

Figure 5 shows overall Stirling system mass with temperature ratio for three heater head temperatures. System mass and performance models were obtained from the target values of the Space Power Free Piston Stirling Engine Program. Just as for the Brayton system, mass first decreases due to

increased efficiency and then increases due to the overriding influence of increasing radiator mass. Total system masses are lower for the Stirling than for the Brayton system. Note that the minimum mass temperature ratios occur at lower values than for the Brayton system. This occurs because the Stirling engine rejects heat at constant temperature and the mean effective radiator temperature is below the lowest cycle temperature. The Brayton cycle, on the other hand, rejects heat at near constant pressure but at temperatures which decrease from recuperator exit to compressor inlet. Hence, the mean effective radiator temperature is well above the lowest cycle temperature.

These studies were conducted for solar dynamic systems with energy storage. Reference 2 compares Stirling and Brayton systems with both nuclear and solar heat input. In all cases the Stirling system, because of its high efficiency, is the lighter system.

#### SPACE POWER DEMONSTRATOR ENGINE (SPDE)

In concert with the Advanced Technology Program a demonstrator engine was built and is currently under test. The engine is called 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 nominal design was 25 kWe from the two opposed-piston Stirling engine - linear alternator system. A photograph of the engine is shown in Fig. 6. The engine is about 1-1/4 m in length and about 1/3 m in diameter. It is suspended from the ceiling by four vertical straps. This flexible suspension was the test configuration and no discernible vibration was observed during operation. Accelerometers mounted on the engine housing indicated maximum amplitudes (peak-to-peak) of less than 0.01 mm which corresponds to a "g" of less than 0.2. A general description of the engine is given in Refs. 3 and 4. Figure 7 is a cross section of half of the engine taken through a line of symmetry. The module shown was designed to produce 12.5 kWe - half the full engine power.

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

The SPDE first developed power in June 1985 at about 4 kWe. Over the past 16 months several modifications were made to both the engine and load in order to increase engine power. Some of the changes include a sintered regenerator, reduced dead volume, separate bearing flow to displacer and power piston (which permits full-stroke operation), and removal of a redundant current protection device (which caused premature shutdown). Currently the engine develops about 25 kW of PV power and 17 kW of electrical power. The PV power is very respectable (28.8 kW was the design goal). However, the alternator efficiency is considerably lower than the design goal of 93 percent. The alternator

efficiency is inversely proportional to the alternator frequency - ranging from about 65 to 70 percent efficiency at 100 Hz to the high eighties at 70 Hz.

Figure 8 shows the relationship between engine and alternator power as a function of piston amplitude under conditions of 150 bar pressure, 100 Hz frequency and at a temperature ratio of two. As shown on the graph the data are very reproducible. The engine efficiency based upon PV power is fairly consistent at around 22 percent. The computer code predictions for engine power and efficiency are within 10 percent of the experimental measurements.

In order to better understand the alternator low efficiency, tests were conducted by electrically energizing the stator coil and removing individual and multiple alternator and alternator structural components to indicate variations in magnetic flux distribution.

The coil was energized with ac input power at various voltage and frequency levels. The components removed in various combinations included alternator stators, alternator plunger, plunger cylinder, pressure vessel, and joining ring. These components and locations can be seen in Fig. 7.

Future static bench tests with ac coil excitation will be conducted by replacing the as-built components with nonmagnetic and low-electrical conductivity material. The intent is to see to what extent the nonmagnetic low-electrical conductivity material replacement measurements correspond to the bare component replacement measurements. The results of the initial component replacement test at 100 Hz are shown in Fig. 9 where about 35 efficiency points are lost in the components. Engine and alternator system tests show the alternator loss to be about 30 efficiency points. The agreement between tests was satisfactory. Similar tests will be repeated at 70 Hz before the replacement tests are conducted.

Components are being assembled to provide two SPDE type test bed engines for conducting advanced component evaluation. The SPDE testing is complete and this engine will be reconfigured to provide two single-cylinder engines. These engines will be referred to as Space Power Research Engines (SPRE) I and II. These engines will have dynamic absorbers since they are no longer inherently-balanced opposed-piston engines. Testing on SPRE I will be conducted at MTI and on SPRE II at NASA Lewis. In no way will the testing be a duplication, but the goal is to attempt to learn more from two test beds. Component testing will include hydrodynamic gas bearings actuated either by rotating a reciprocating piston with an electric motor or with turbine blades energized by swirling compression space gas. Heat-pipe heater heads will replace the molten salt shell-and-tube heat exchangers. Modular type heat exchangers including heater, regenerator and cooler will also be evaluated. Alternator efficiency improvement tests will also be conducted on SPRES and on bench tests.

Figure 10 lists some of the significant accomplishments and findings from the SPDE testing. Keep in mind that this engine was not designed for space applications, but was designed to demonstrate certain perceived free-piston Stirling engine potential attributes. Time and budget were

critical. Listed in Fig. 11 are some of the free-piston Stirling state-of-the-art technology extensions that occurred as a result of the SPDE demonstration. Excellent opposed-piston dynamic balancing was one achieved objective; and engine performance at a temperature ratio of two was significant. Under these conditions ( $T_r = 2$ ) not only is the Carnot cycle efficiency low - 50 percent, but the percent of Carnot that is achievable decreases as the Carnot efficiency is reduced. Although externally pumped gas bearings were employed, there is no doubt that internally actuated gas bearings can and will be successful.

#### 25 kWe STIRLING SPACE ENGINE (SSE)

Under NASA SP-100 Advanced Stirling Technology funding, Sunpower, Inc., with consultation provided by MTI, completed a conceptual design of a single-cylinder, 25 kWe free-piston Stirling engine linear alternator (FPSE/LA) system. The detail design, fabrication, and check-out testing will be conducted under a separate competitive procurement. Some of the benefits that should result from this 1050 K engine are listed in Fig. 12. The conceptual design was the first free-piston in the 25 kWe class designed specifically for a space power Stirling engine linear alternator system. A requirement in the design was not to use refractory alloys but limit the design to superalloy materials. As a result, for the 7-yr life design requirement, the temperature of the heater was limited to 1050 K at a temperature ratio of two. Heat pipes were chosen for the hot end heat transport system and a pumped loop was selected for the heat rejection system. A reference design and an experimental research design were both conceptually carried along. The reference design will incorporate improvements as they evolve from the supporting research technology being carried out. The experimental design will include research instrumentation and bolted flanges so that the engine can be readily disassembled for modifications and inspections and measurements. Figure 13 is a schematic cross section of the initial conceptual design. The targeted specific mass is less than 6 kg/kW with greater than 25 percent system efficiency when generating 25 kW of electrical power (see first milestone on Fig. 2).

One important feature of this engine is the simplified modular heat-pipe heater-regenerator-cooler assembly. The SPDE design used about 3200 heater tubes and 3800 cooler tubes that now are replaced by about 40 modular assemblies. One module is shown in Fig. 14. Referring to the lower assembly and going from right to left, there is the heat-pipe heater showing the gas side fins for enhanced heat transfer, the regenerator, and finally, the cooler with, again, gas-side fin-surface augmentation. The upper assembly is the containment tube to house the heat exchangers. The heat-pipe portion of the heater does not fit into the containment tube. The raised cylindrical surface between the heat-pipe and the heater fins is where the module is joined to the engine pressure vessel.

The frequency of the engine will probably be slightly less than 100 Hz and the mean pressure level about 180 bar. This engine will use liquid metal in the heat-pipe - currently planned to be sodium. There will be an active dynamic balance system. Figure 13 conceptually shows the current thinking of size and location of the balance unit.

Hydrodynamic bearings will be used for both the power piston/alternator plunger and displacer. However, the method of developing the hydrodynamic film need not be the same for each component. The temperature level of the heater (1050 K) is about 400 K above the highest temperature used on the SPDE original design and build.

#### SUMMARY

The space power demonstrator engine (SPDE) served a very useful and important part in free-piston Stirling technology development for space power application. The engine developed 25 kW of PV power, has operated successfully for over 300 hr at temperature ratio's as low as two and demonstrated PV engine efficiency of around 22 percent. Although the alternator efficiency dropped off rapidly with increasing frequency, measurements indicate where most of the losses occur; and it is felt that improving the alternator efficiency is an engineering problem with an early solution. A technological breakthrough is not needed. Nevertheless, even with the inefficient alternator, 17 kW of electrical power was delivered to the system load.

Even more encouraging is the fact that the computer code predictions for engine power and efficiency are within 10 percent of the experimental measurements. By converting the SPDE into two 12.5 kW test beds provides an efficient utilization of manpower and dollars. Figure 15 summarizes some of the significant accomplishments over the last year.

A 25 kWe single-cylinder Stirling space engine conceptual design is complete. The design incorporates many advanced design features required for a

prototypic flight engine. This engine uses super alloy materials and, wherever possible, uses concepts and components also applicable for refractory metal (1350 K) application. This design features modular heat exchangers with sodium heat pipes, thereby, dramatically reducing the number of joints and enhancing the heat transfer capability.

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

#### REFERENCES

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3. Dochat, G.R., "Free-Piston Stirling Engines for Space Power," Proceedings of the Twenty-Second Automotive Technology Development Contractor's Coordination Meeting, Society of Automotive Engineers, Warrendale, PA, 1984, pp. 209-213.
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- IS A LONG RANGE BROADLY BASED PROGRAM
- SUPPORTS KEY TECHNOLOGY AREAS NEEDED FOR:
  - GAS BEARINGS
  - LINEAR ALTERNATORS
  - HEAT EXCHANGERS
  - MATERIALS
  - POWER CONDITIONING INTERFACE
  - OSCILLATING FLOW
  - PERFORMANCE PREDICTIONS

FIGURE 1. - NASA SP-100 ADVANCED STIRLING TECHNOLOGY PROGRAM.

- DEMONSTRATE PERFORMANCE BY END OF FY 91 OF 1050 °K SINGLE CYLINDER BALANCED ENGINE WHICH INCLUDES:
  - 25 kWE
  - > 25 PERCENT EFFICIENCY
  - < 6 kg/kWE
- DEMONSTRATE ONE YEAR OF SUCCESSFUL SIMULATED SPACE CONFIGURATION (1050 °K) OPERATION BY END OF FY 92
- ESTABLISH TECHNOLOGY FEASIBILITY OF 1350 °K ENGINE COMPONENTS INCLUDING HEAT-PIPE HEATER HEAD, HYDRODYNAMIC BEARINGS, MATERIALS JOINING AND ALTERNATORS BY END OF FY 92
- COMPLETE DETAIL DESIGN OF 1350 °K ENGINE AT  $T_r > 2$  BY END OF FY 92

FIGURE 2. - STIRLING ADVANCED TECHNOLOGY PROGRAM MAJOR MILESTONES.

- HIGH EFFICIENCY (RELATIVE TO OTHER SYSTEMS)
- POTENTIAL FOR LONG LIFE AND HIGH RELIABILITY
- NONCONTACTING GAS BEARINGS
- FEW MOVING PARTS
- COMPATIBLE WITH SOLAR OR NUCLEAR MISSIONS
- DYNAMICALLY BALANCED
- NO ROD SEALS
- NO OIL INSIDE ENGINE
- POTENTIAL FOR GRACEFUL DEGRADATION
- POWER OUTPUT FLEXIBILITY

FIGURE 3. - WHY FREE-PISTON STIRLING FOR SPACE POWER?

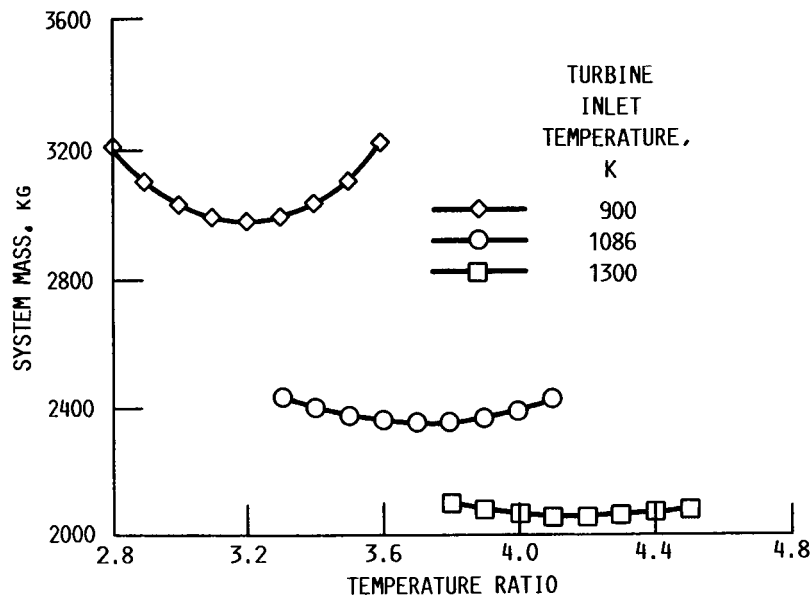


FIGURE 4. - SOLAR BRAYTON SYSTEM MASS SENSITIVITY TO TEMPERATURE RATIO, 35 kWe.

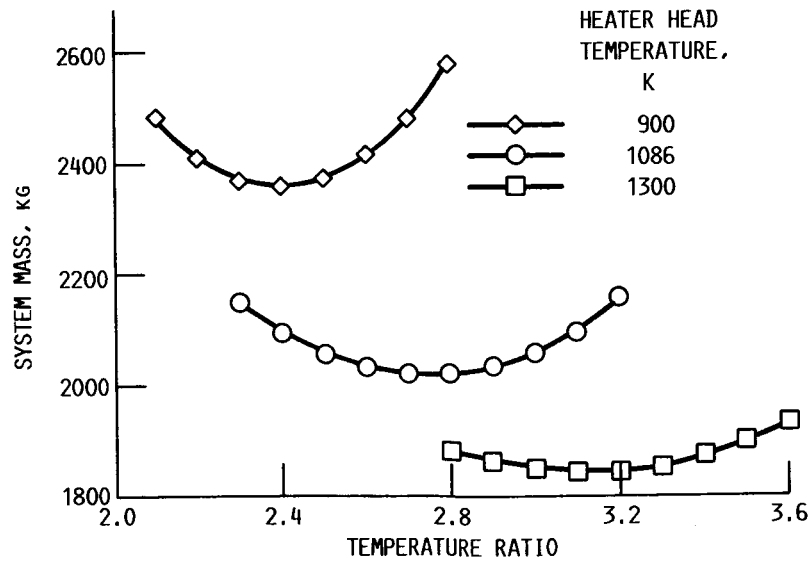


FIGURE 5. - SOLAR STIRLING SYSTEM MASS SENSITIVITY TO TEMPERATURE RATIO, 35 kWe.

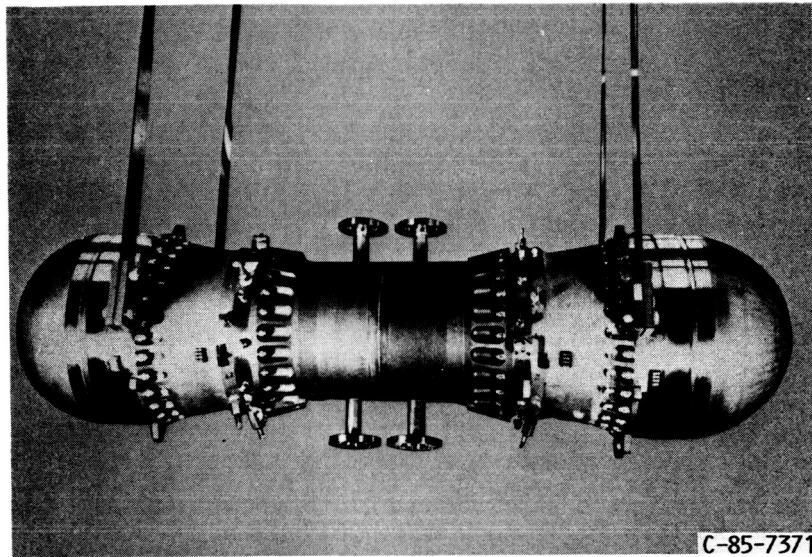


FIGURE 6. - 25 kW SPACE POWER DEMONSTRATOR ENGINE (SPDE) AT  
MECHANICAL TECHNOLOGY INC.

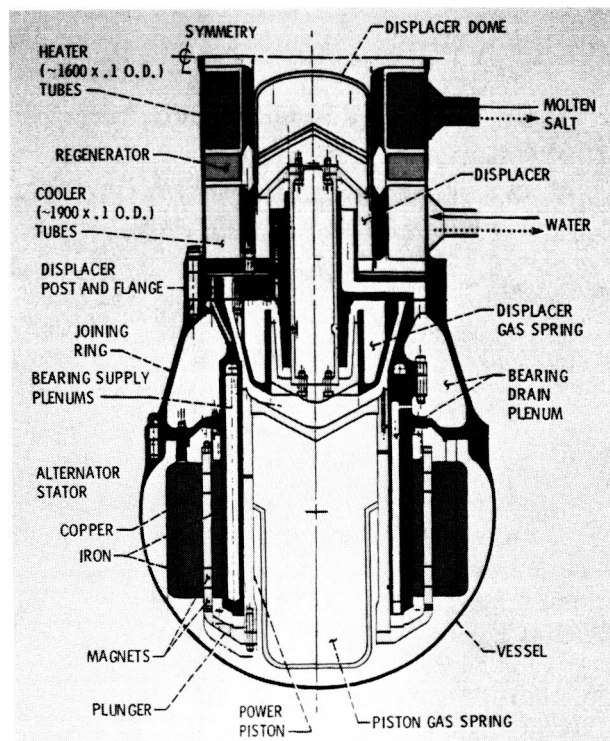


FIGURE 7. - HALF OF 25 kW SPDE.



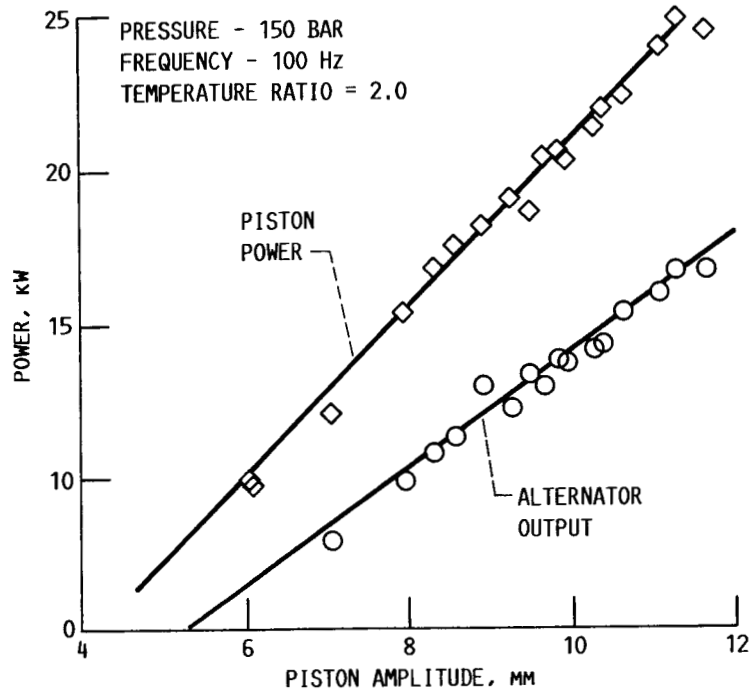


FIGURE 8. - SPDE ENGINE TESTS - OCTOBER 24, 1986.

- ALTERNATOR EFFICIENCY IS SIGNIFICANTLY BELOW DESIGN (70 PERCENT VERSUS 93 PERCENT)
  - FLUX LEAKAGE TO SURROUNDING STRUCTURE AT HIGH FREQUENCY IS INDICATED
  
- MEASUREMENTS AT 100 HERTZ IDENTIFY LOSSES IN:
 

● CYLINDER	9.5 EFFICIENCY POINTS
● JOINING RING	9.3
● STATORS	6.3
● PRESSURE VESSEL	5.5
● PLUNGER	4.2
● TUNING CAPACITORS	0.2
  
- TOTAL MEASURED EFFICIENCY; POINT LOSSES 35
  
- ENGINE/ALTERNATOR TEST EFFICIENCY; POINT LOSSES 30

FIGURE 9. - SPACE POWER DEMONSTRATOR ENGINE - PROBLEM AREA.

- CODES PREDICT ENGINE POWER AND EFFICIENCY; WITHIN  $\pm 10$  PERCENT
- LINEAR ALTERNATOR - SUPPORT STRUCTURAL LOSSES VERY SENSITIVE TO FREQUENCY
- IMPORTANCE OF HEAT EXCHANGERS AND REGENERATORS
- TEMPERATURE RATIO BELOW 2.0 UNDESIRABLE
- GAS BEARING OPERATION ATTRACTIVE
- EXCELLENT DYNAMIC BALANCE
- DIMENSIONAL STABILITY OF BERYLLIUM COMPONENTS

FIGURE 10. - WHAT HAVE WE LEARNED FROM SPDE?

- PRESSURE - 60 BAR TO 150 BAR
- FREQUENCY - 60 Hz TO 100 Hz
- PISTON DIAMETER - 4 IN. TO 5 IN.
- TEMPERATURE RATIO - 3.0 TO 2.0
- GAS BEARINGS
- DYNAMICALLY BALANCED
- PISTON POWER SCALE UP - 3 kWe TO 12.5 kW
- ENGINE SCALE UP - 3 kW TO 25 kW
- HOME GROWN TECHNOLOGY
- CODE DEVELOPEMENT AND VALIDATION

FIGURE 11. - FREE-PISTON STATE-OF-THE-ART SPDE TECHNOLOGY EXTENSION.

- FIRST STIRLING DESIGNED FOR SPACE
- SIMPLIFIED DESIGN - LESS JOINTS
- POTENTIAL HIGH SPECIFIC POWER SYSTEM
- DESIGN BASIS FOR 1300 K REFRACTORY ENGINE
- TECHNOLOGY ENABLES SIGNIFICANT GROWTH FOR SOLAR DYNAMIC POWER APPLICATION
- ADVANCES IN TECHNOLOGY TO IMPROVE PERFORMANCE AND RELIABILITY

FIGURE 12. - WHAT DOES 1050 K STIRLING ENGINE GIVE?

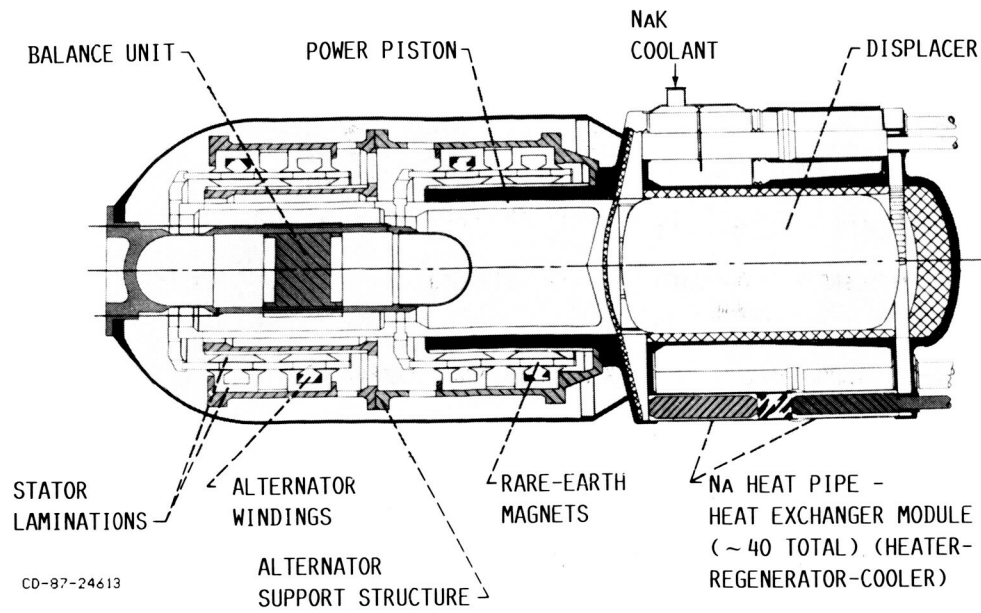


FIGURE 13. - SUPERALLOY STIRLING SPACE ENGINE (SSE) REFERENCE SPACE DESIGN.

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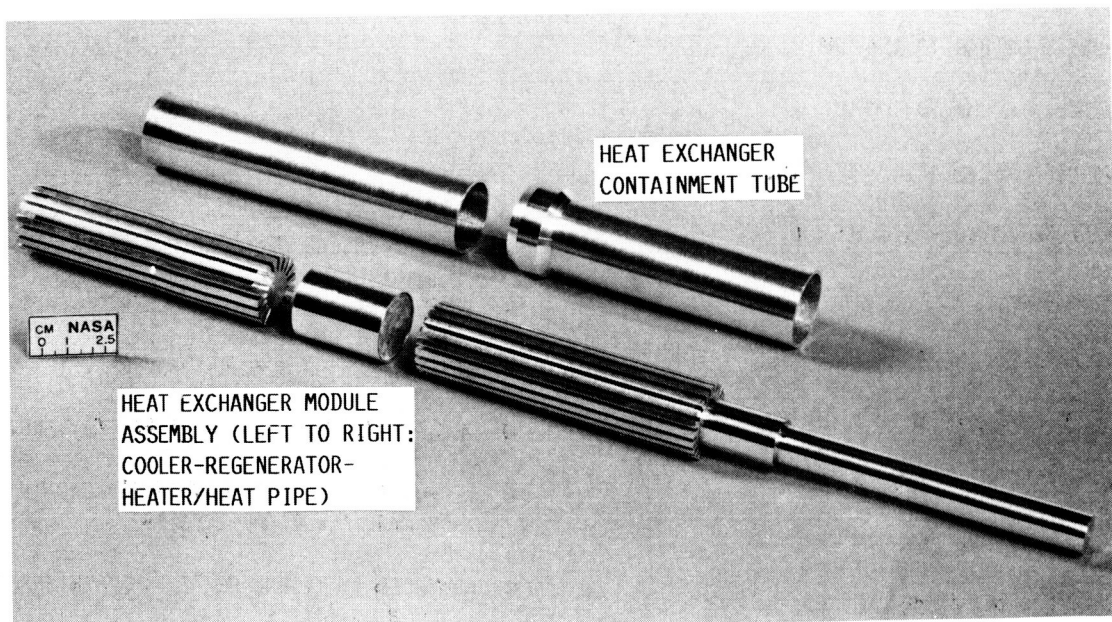


FIGURE 14. - STIRLING MODULAR HEAT EXCHANGER ASSEMBLY.

- SPDE PERFORMED WELL - TESTING COMPLETE
  - STIRLING PV POWER - 25 kW
  - ALTERNATOR ELECTRICAL - 17 kW
  
- 1050 K STIRLING SPACE ENGINE PRELIMINARY DESIGN  
NEARING COMPLETION
  
- ADVANCED RESEARCH PROGRAMS WELL UNDERWAY
  
- CODE VALIDATION - HARMONIC CODE LOOKS EXTREMELY  
PROMISING

FIGURE 15. - SUMMARY.

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		10. Work Unit No.	
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16. Abstract <p>An overview is presented of the National Aeronautics and Space Administration (NASA) Lewis Research Center free-piston Stirling engine activities directed toward space-power application. Free-piston Stirling technology is applicable for both solar and nuclear powered systems. As such, NASA Lewis serves as the project office to manage the newly initiated NASA SP-100 Advanced Technology Program. This 5-yr program provides the technology thrust for providing significant component and subsystem options for increased efficiency, reliability and survivability, and power output growth at reduced specific mass. One of the major elements of the program is the development of advanced power conversion concepts of which the Stirling cycle is a viable growth candidate. Under this program the status of the 25 kWe opposed-piston Space Power Demonstrator Engine (SPDE) is presented. Included in the SPDE discussion are comparisons between predicted and experimental engine performance, enhanced performance resulting from regenerator modification, increased operating stroke brought about by isolating the gas bearing flow between the displacer and power piston, identifying excessive energy losses and recommending corrective action, and a better understanding of linear alternator design and operation. Technology work is also conducted on heat exchanger concepts, both design and fabrication, to minimize the number of joints as well as to enhance performance. Design parameters and conceptual design features are also presented for a 25 kWe, single-cylinder free-piston Stirling space-power converter. A cursory comparison is presented showing the mass benefits that a Stirling system has over a Brayton system for the same peak temperature and output power.</p>			
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