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1988 Overview of Free-Piston Stirling Technology for Space Power at the NASA Lewis Research Center

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1988 OVERVIEW OF FREE-PISTON STIRLING TECHNOLOGY FOR SPACE POWER AT THE NASA LEWIS RESEARCH CENTER

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ABSTRACT

An overview is presented of the National Aeronautics and Space Administration (NASA) Lewis Research Center free-piston Stirling engine activities directed toward space power. NASA Lewis serves as the Project Office to manage the NASA SP-100 Advanced Technology Program. One of the major elements of the Advanced Technology Program is the technology development of advanced power conversion concepts of which the Stirling cycle is an attractive growth candidate.

Discussed in this paper is the completion of the Space Power Demonstrator Engine (SPDE) testing - terminating with the generation of 25 kW of engine power from a dynamically-balanced opposed-piston Stirling engine at a temperature ratio of 2.0. Engine efficiency was greater than 22 percent. The SPDE recently has been divided into two separate single-cylinder engines, Space Power Research Engine (SPRE), that now serve as test beds for the evaluation of key technology disciplines. These disciplines include hydrodynamic gas bearings, high-efficiency linear alternators, space qualified heat pipe heat exchangers, oscillating flow code validation, and engine loss understanding. The success of the SPDE at 650 K has resulted in a more ambitious Stirling endeavor - the design, fabrication, test, and evaluation of a designed-for-space 25 kW per cylinder Stirling Space Engine (SSE) to operate at a hot metal temperature of 1050 K using superalloy materials. This design is a low temperature confirmation of the 1300 K design. It is the 1300 K free-piston Stirling power conversion system that is the ultimate goal. The approach to this goal is in three temperature steps. However, this paper concentrates on the first two phases of this program - the 650 K SPDE and the 1050 K SSE.

INTRODUCTION

The Lewis Research Center of the National Aeronautics and Space Administration (NASA) started work on free-piston Stirling engines around 1977. Today, approximately 16 professionals are engaged in free-piston Stirling technology at NASA Lewis. These free-piston projects include: (1) NASA SP-100 Advanced Stirling Technology Project, which will comprise the major emphasis of this paper; (2) Department of Energy (DOE) - Sandia National Laboratory (SNL) - an interagency agreement with NASA Lewis to develop Stirling engine technology for terrestrial solar energy conversion. This project called Advanced Stirling Conversion Systems (ASCS) is based upon using current technology to demonstrate a system on-sun generating 25 kW of electricity at DOE's long-term cost goals; and (3) Stirling Power Generating Systems Project - DOE - Oak Ridge National Laboratory (ORNL) - a Stirling technology interagency agreement with NASA Lewis and based upon the synergistic characteristics between space power and residential/commercial heat pumps. These characteristics include high efficiency, low vibration, potential for long life and high reliability, and independence of heat source or fuel.

Due to a length constraint, the discussion contained in this paper will be limited to the NASA SP-100 Advanced Stirling Technology Project. However, Ref. 1 presents a description of the ASCS project.

NEED FOR SPACE POWER

NASA's space power technology history has concentrated on systems delivering less than 10 kW, as shown in Fig. 1. The exception was Skylab, which was designed to deliver nearly 20 kW to the user. Power requirements of NASA's missions, in the past, have been met almost exclusively by photovoltaic (PV) and electrochemical storage systems. NASA Lewis, as the primary NASA center for space power research and technology, has contributed significantly to these technologies. Only recently, we have expanded our research into technologies which offer promise of 100's to 1000's of kW of electrical power in space.

These expanded research areas cover a broad base of advanced technology. The first step toward this research and technology advancement is through the Civil Space Technology Initiative (CSTI). This 5-year technology program is the precursor to NASA's bold new missions. The technology resulting will enable and greatly enhance NASA missions while restoring the Agency's technical capability. The CSTI program not only focuses on space power but also on transportation systems, operations, and science. CSTI started in 1988 and will be augmented in 1989 by another technology program called Pathfinder. Pathfinder will continue the technology recovery and build upon the base initiated in CSTI - reestablishing NASA's leadership role. Whereas CSTI focuses on earth orbiting missions, Pathfinder will focus on space explorations; a return to the moon and missions to Mars. CSTI will end in 1992 and at that time should have generated critical data from which the Agency can make decisions on new initiatives. It is these bold initiatives, the first steps being the CSTI and Pathfinder programs, that require the large amounts of space power shown in Fig. 1. One space power system candidate for these bold missions is the free-piston Stirling engine.

The free-piston Stirling is a rapidly emerging technology which has only recently attracted considerable attention because of the successful Space Power Demonstrator Engine (SPDE). A recent scaling study indicates that it may be possible to build a free-piston Stirling engine/linear alternator system with 150 kWe per cylinder capability. Less than 5 years ago it was considered a major achievement to build and successfully operate a 3 kW free-piston Stirling engine.

STIRLING ADVANCED TECHNOLOGY PROJECT

The Stirling Advanced Technology Project is a significant segment of the NASA SP-100 Advanced Technology Program. The objective of the Stirling technology activity is to demonstrate the capability needed to proceed toward development of space qualified free-piston Stirling engine technology to meet future mission needs. Systems studies have been conducted that show the growth potential of Stirling-space-power conversion systems when operated at peak temperatures of 1300 K. As a result, engine hardware demonstrations are planned at 3 temperature levels, 650, 1050, and 1300 K. The 650 K engine was the Space Power Demonstration Engine (SPDE) which was designed without all desired space-power innovations - such as heat-pipe heat exchangers. Beryllium, however, was used for the reciprocating pistons and low specific mass-high power density was a goal. The success of the SPDE engine is the basis for a Stirling power conversion system to be designed to meet space power requirements. The design will ultimately be for a 1300 K application using refractory metals and/or ceramic components. However, because of the expense associated with an engine of this technology advancement (1300 K temperature, nonconventional materials, and a unique test environment) a lower temperature concept was chosen for the first space test engine. This concept uses 1050 K as the peak temperature, thereby enabling superalloy materials - rather than refractory materials - to be used. This engine is called the Stirling Space Engine (SSE). It is anticipated that except for materials and modest changes, the two designs (1300 and 1050 K) will be similar. During the design and fabrication of the 1050 K engine, component advancement will be conducted in the areas of heat-pipe heat exchangers, efficient linear alternators, gas bearings, code development and validation, and long-term life and reliability. The near-term major objectives, including hardware and technology advancements, are as follows: (a) demonstrate performance of the 1050 K single cylinder SSE engine including 25 kW of electrical power at an efficiency greater than 25 percent (electrical power out divided by heat into the engine) and a specific mass including engine and alternator of less than 6 kg/kWe; (b) demonstrate 1 year of successful operation at above conditions; (c) establish technology feasibility of 1300 K engine components including heat-pipe heater heads, hydrodynamic bearings, materials joining, and high efficiency alternators; and (d) complete a design of a 1300 K Stirling at a temperature ratio of 2. In-house technology activities are being conducted at NASA Lewis to enhance the efforts done under government contracts.

COMPLETION OF SPDE TESTING

Two and one-half years ago, in Rome, I spoke of early data from the SPDE. At that time it was difficult to get more than 12 kW from the engine. Today SPDE no longer exists as an opposed-piston 2 cylinder engine. The engine, after successful operation, has been cut in half - one half is under test at NASA Lewis and the other half at the contractor site, Mechanical Technology Inc. (MTI) in Latham, NY. These engines are now called Space Power Research Engines (SPRE). The engines now are serving as test beds for the evaluation of key technology areas including hydrodynamic gas bearings, high efficiency linear alternators, heat-pipe heaters, engine loss understanding, 1050 K operation, improved efficiency, and enhanced components.

In completing testing of the SPDE some significant changes enabled the engine to operate at full stroke, a temperature ratio of 2.0 while developing about 25 kW of engine power at an engine efficiency of 22 percent. Engine power for this report is defined as the power delivered to the piston from the compression space; engine efficiency is defined as the engine power defined above divided by the sum of the power rejected in the cooler plus the engine power. References 2 and 3 describe the SPDE in more detail than presented in this overview paper. The above definitions have been used because at 100 Hz operation, the linear alternator was only about 65 to 70 percent efficient, and at 70 Hz the efficiency was in the high eighties. The alternator efficiency is inversely proportional to the alternator frequency. 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. 2.

Future static bench tests with ac coil excitation will be conducted by replacing the as-built components with nonmagnetic and low-electrical conductive material. The intent is to see to what extent the nonmagnetic and 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. 3 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. These measurements showed that about 2/3 of the inefficiency was manifested in eddy current losses; the remainder being materials hysteresis losses. We currently believe that we understand the alternator problem and are in the process of conducting additional bench tests, both in-house and on contract, to evaluate improved alternator concepts and materials selection. Even though the alternator was inefficient, SPDE generated 17 kW of electrical power - an overall efficiency of about 15 percent.

The changes that enabled the engine to develop almost full-design power included; (a) an improved regenerator (although not the optimum - but one that maintained integrity during testing). Reference 4 discusses failure of regenerator screens in a high frequency Stirling engine; and (b) separate/uniform hydrostatic bearing flow to the reciprocating pistons (2 displacers and 2 power pistons). The alternator inefficiency resulted in heat being generated in the piston cylinder. As a result, the cylinder expanded relative to the power piston and the flow of bearing gas from a single supply source predominantly went to the reduced flow restriction - the increased gap between piston and cylinder and consequently starved the flow to the displacer bearing. As a result, the displacer no longer had a hydrostatic bearing and rubbing of the displacer rod resulted. Thus, the engine could not operate efficiently or at full stroke. At present, hydrodynamic gas bearings are being evaluated to improve efficiency, enhance hardware simplicity, and provide more design flexibility.

Before going into the SPRE project, it is important to point out what has been learned from the SPDE demonstration. The following is a short summary of some of the significant accomplishments.

The recognition of the linear alternator support structure losses was very important, particularly as the alternator frequency increased. The ability of the codes to predict engine power and efficiency within plus or minus 15 percent was important - particularly at temperature ratios of two. Initial power shortfall highlighted the importance of heat exchangers and regenerator design. Gas bearing operation is very attractive for reciprocating pistons even though the engine-actuated hydrodynamic concept has not been completely demonstrated. One feature of SPDE that was quite significant was the dynamic balance resulting from the operation of two opposed-piston cylinders. The pressure vessel vibration was barely perceptible - not unlike the refrigerator in your home.

SPRE PROJECT

In May of 1987 MTI completed the acceptance test of the SPRE engine. As previously mentioned, the SPRE is SPDE cut in half with end caps covering the expansion space ends where the severing cut was made. The end cap reduced the dead volume in the expansion space, thereby increasing power. In addition, clearance seals were improved to that of the original design. Both of these changes were in the direction of enhanced performance. Figure 4 shows some of the MTI acceptance-test results. Engine power is shown as a function of piston amplitude. The total power piston stroke is twice the piston amplitude. Over the range of engine power efficiency increased from about 20.5 percent at 5 kW to around 22.5 percent at 13 kW. This SPRE engine configuration was delivered to NASA in June 1987 and the acceptance tests were repeated. The engine has been installed in the test cell at NASA and is shown in Fig. 5. Note the large ballast mass to absorb the engine unbalance when the engine is operated as a single cylinder. One of the first tests to be conducted at NASA is to determine the amount of power consumed in a balancing device which replaces the large ballast mass.

Depending upon whether an active or passive balancing system is employed, the mass penalty may range between 3 to 10 percent. Sunpower Inc. of Athens, Ohio successfully designed, built, and tested a passive balancing unit for a 1 kW free-piston Stirling at NASA Lewis. MTI has also demonstrated a dynamic passive balancer for a 3 kW free-piston Stirling engine.

The logic behind having two engines at two test sites is to increase research productivity - not duplicate testing. Currently, MTI is concentrating on a hydrodynamic bearing on the power piston; conducting bench dynamometer alternator tests (to assess the affect of support structure, engine component materials, and alternator configuration); and modifying the SPRE heater. The heater modification is intended to achieve two objectives. One is to use sodium heat pipes in the heater assembly. The second is to upgrade the heater temperature capability to 1050 K from SPDE 650 K. The major MTI effort is to obtain early evaluation of critical type hardware for the Stirling Space Engine (SSE) build. The goal is to operate an upgraded SPRE at 1000 to 1050 K for a year or until the SSE engine is ready for test. Incorporated into the upgraded SPRE are hydrodynamic gas bearings, sodium heat pipes, and an improved alternator.

SSE PROJECT

The Stirling Space Engine is an engine design based upon 1300 K operation, but one that will be fabricated initially from superalloy materials and run at 1050 K to confirm design features. Sunpower provided the initial SSE conceptual design. This 1050 K engine, called SSE, will serve as a transition from demonstrating Stirling technology feasibility at 650 K peak temperature to 1050 K. The transition will incorporate advanced heat exchangers using sodium heat pipes to significantly reduce the number of fabrication joints in the engine. Hydrodynamic gas bearings will be used for the piston and displacer and an improved alternator design will be used to reduce the losses encountered during SPDE testing. The success of the 1050 K engine may play an important role in various space-power programs. For example, a successful Stirling at 1050 K may necessitate that Stirling be given a closer look for future Space Station missions. Also, dependent upon the SP-100 reactor and thermoelectric converter progress, Stirling may deserve another look as a near-term option; as well as a growth consideration.

LOSS UNDERSTANDING

In general, the accuracy of Stirling engine computer codes in predicting the thermodynamic performance of engines has left a lot to be desired - particularly codes which have not been calibrated. Existing design codes are good enough to design engines that work. However, in order to get engines to perform well, expensive hardware modifications are usually needed. One of the main reasons for this problem is the lack of proper characterization of thermodynamic losses that occur inside the engine. There is even much disagreement as to which losses are the major losses. In order to resolve this lack of understanding and to generate more accurate design and performance codes a Stirling engine loss understanding effort has been started by NASA Lewis to address characterization of engine thermodynamic losses. There are both contracts and grants in place investigating loss mechanism areas. Figure 6 is a schematic layout showing locations of heat transfer and fluid flow problem areas. Areas that have been identified as requiring better characterization are: (a) instantaneous heat transfer rates in the heat exchangers; (b) adiabatic losses - which are described as losses due to mixing of gases at different temperatures and losses which occur when a nearly adiabatic volume is adjacent to a surface in which significant heat transfer occurs; (c) flow maldistributions - deviations from one dimensional flow resulting from poor manifolding; (d) instantaneous heat transfer rates in gas springs, compression and expansion spaces (this heat transfer causes a hysteresis power loss); (e) appendix gap losses; (f) net energy flux per cycle through the regenerator - from heater to cooler; (g) area transition heat transfer and pressure drop; and (h) instantaneous pressure drop across the displacer, power piston, and viscous dissipation. Contractual loss understanding efforts are being performed at MTI, Sunpower, the University of Minnesota (two grants), Case Western Reserve University in Cleveland, Ohio, and Gedeon Associates of Athens, Ohio. A more thorough treatment of the above mentioned loss understanding mechanisms is given in Ref. 5.

FREE-PISTON SCALING

MTI, under contract to NASA Lewis, has conducted a scaling study to analyze high-power free-piston Stirling engines for use in future new initiative space-power system missions. The power level needs for these missions were previously pointed out in Fig. 1. The purpose of the study was two-fold: one to determine whether it was design feasible to build a single cylinder free-piston Stirling engine linear alternator system at a power level of 150 kWe; and secondly to determine parametric relationships between efficiency and specific mass over a range of power output (25 to 150 kWe per cylinder) and temperature ratios of 1.7 to 3.0.

Three different heat exchanger configurations were investigated. An important interim conclusion was that each concept scaled to 150 kWe with acceptable mass and efficiency.

Future work under this contract will investigate the upper power limit per cylinder. The parametric results conducted indicate that efficiency is primarily a function of specific mass and temperature ratio and only a weak function of power level.

CONCLUDING REMARKS

Although Stirling technology is an emerging technology, there is considerable justified interest as to its potential candidacy for space-power missions whether in the tens of kW range or the multi-megawatt range. In less than 5 years, under limited funding, the free-piston Stirling accomplishments have been significant. An opposed piston engine has generated 25 kW of engine power while the engine efficiency was greater than 22 percent at a temperature ratio of 2.0. Engine vibration is exceedingly low. The integrated concept uses a linear alternator and provides a compact power conversion system. Externally pumped gas bearings were used to demonstrate proof of concept. Results of a scaling study show that single cylinder engines are feasible at power levels as high as 150 kW. The upper limit is currently under investigation.

There appears to be no technological break through needed - only verification of system reliability and life and the timely solution of engineering problems in the areas of high efficiency linear alternators; hydrodynamic gas bearings for the reciprocating components; heat-pipe heater heads for either nuclear or solar powered systems; and validation of design and performance codes over the complete range of desired power.

A 1050 K engine design is underway and the design - with the exception of materials substitution - should be applicable for 1300 K application. The 1050 K engine will be subjected to an endurance test which will go a long way toward establishing credibility for Stirling space power. The codes for design and performance predictions are constantly being upgraded through fundamental understanding of engine losses.

REFERENCES

1. Shaltens, R.K.: Comparison of Stirling Engines for Use With a 25-kW Dish-Electric Conversion System, AIAA Paper 87-9069, Aug. 1987. (DOE/NASA/33408-2, NASA TM-100111.)

2. Dochat, G.R.: Free-Piston Stirling Engine 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.

3. Slaby, J.G.: Overview of Free-Piston Stirling SP-100 Activities at the NASA Lewis Research Center, NASA TM-87224, 1986.

4. Hull, D.R., Alger, D.L., Moore, T.J., and Scheuermann, C.M.: Fatigue Failure of Regenerator Screens in a High Frequency Stirling Engine, NASA TM-88974, 1987.

5. Tew, R.C., Jr.: Overview of Heat Transfer and Fluid Flow Problem Areas Encountered in Stirling Engine Modeling, NASA TM-100131, 1988.

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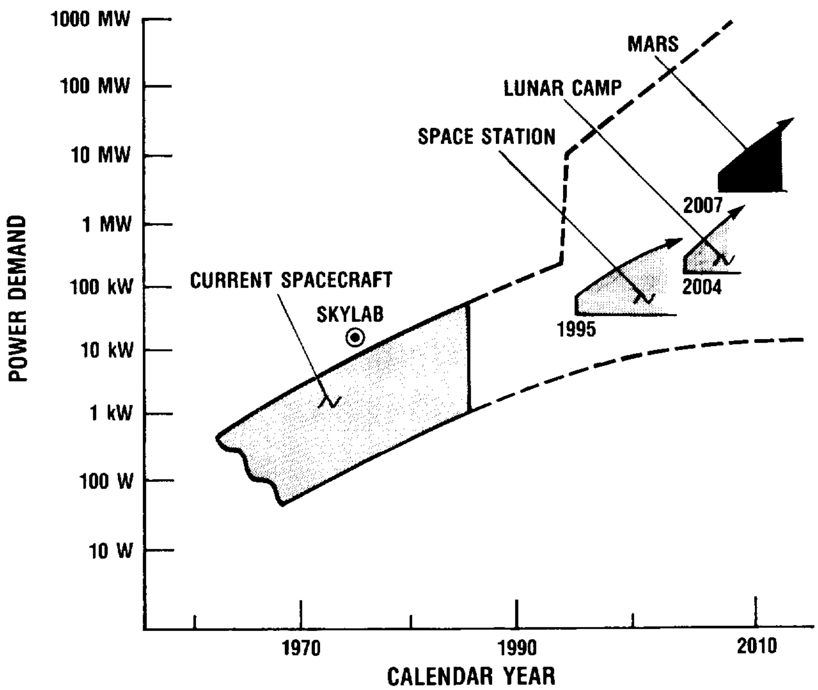

FIGURE 1. - PROJECTED GROWTH IN SPACE POWER.

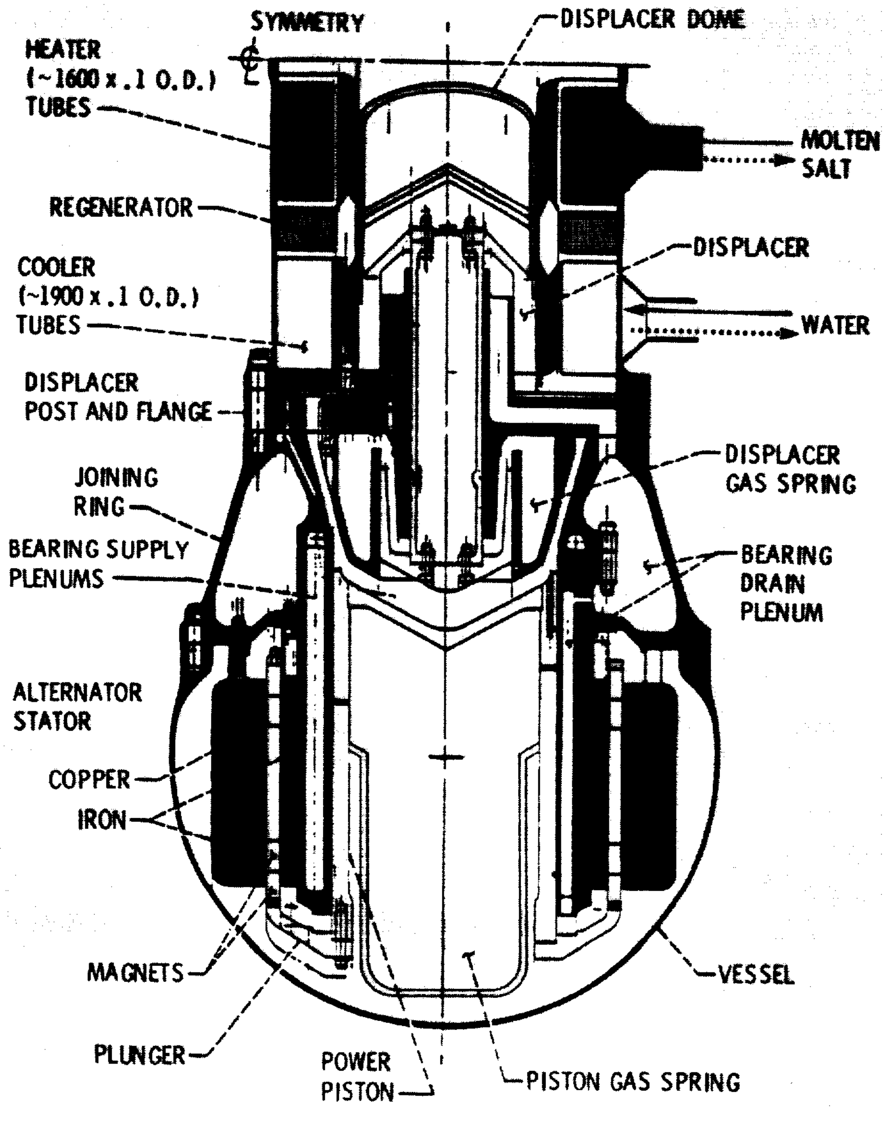

FIGURE 2. - HALF OF 25 kWe SPDE.

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- 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 3. - SPACE POWER DEMONSTRATOR ENGINE - PROBLEM AREA.

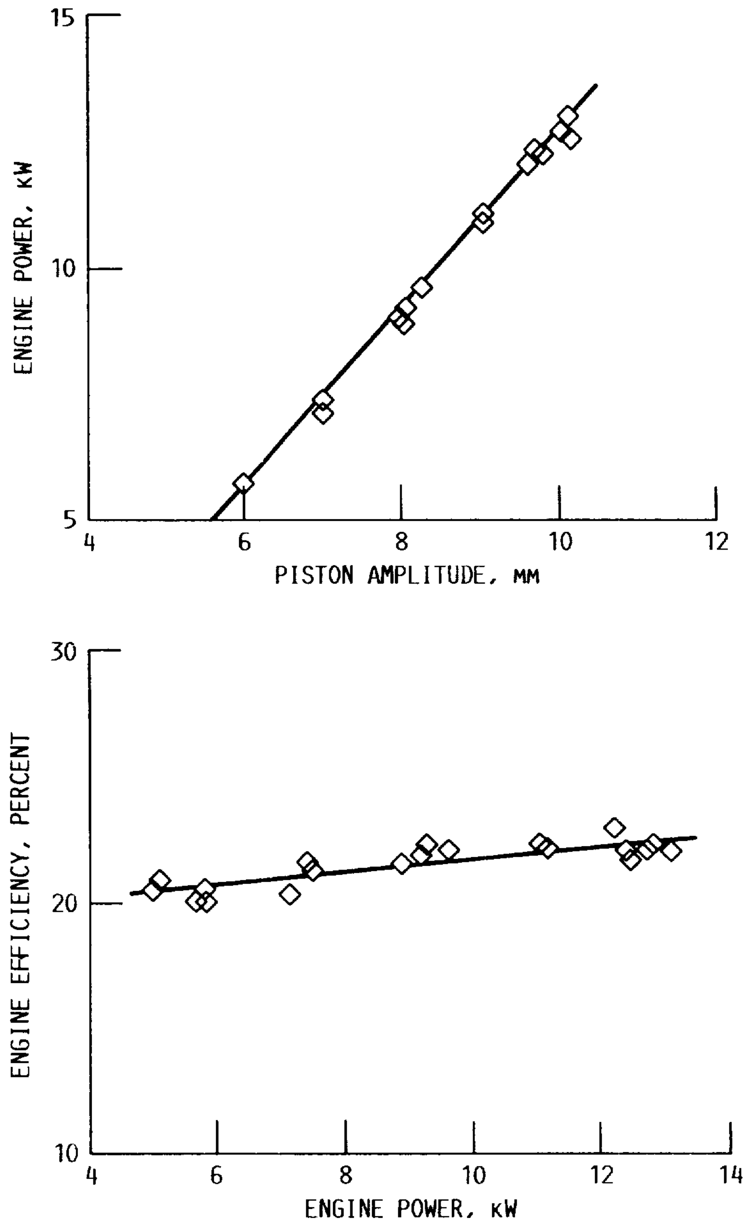

FIGURE 4. - SPACE POWER RESEARCH ENGINE PERFORMANCE AT 150 BAR AND TEMPERATURE RATIO OF 2.0. 5/21/87 TEST DATA.

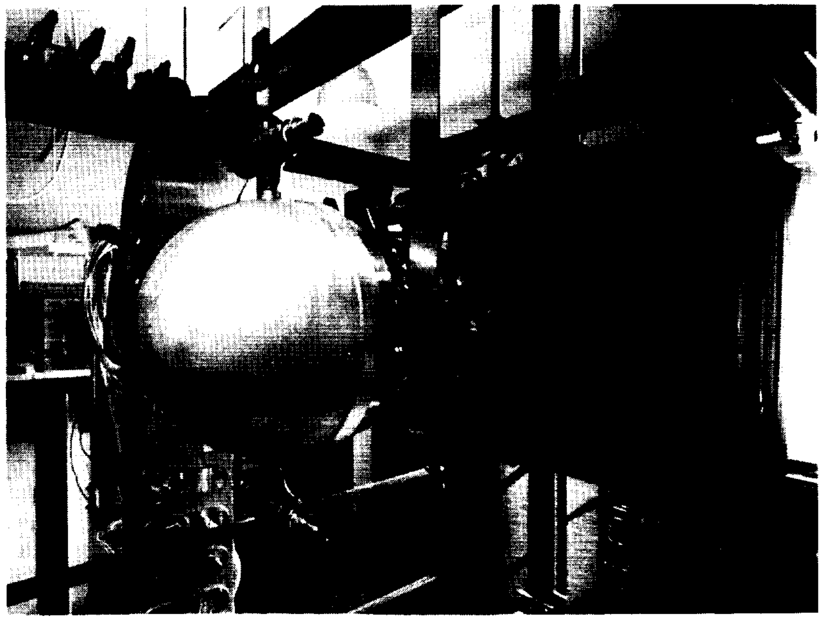

FIGURE 5. - SPACE POWER RESEARCH ENGINE UNDER TEST AT NASA-LERC.

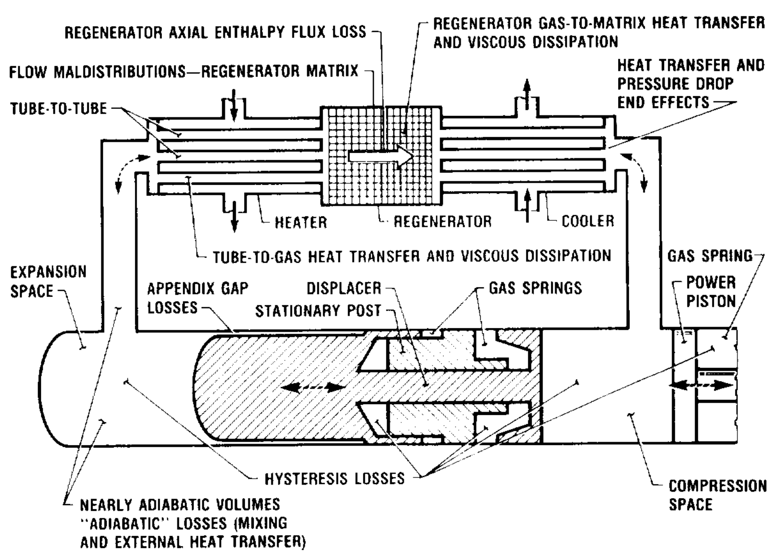

FIGURE 6. - STIRLING ENGINE SCHEMATIC WITH LOCATIONS OF HEAT TRANSFER AND FLUID FLOW PROBLEM AREAS.

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