NASA Technical Memorandum 100241

SPRE I Free-Piston Stirling Engine Testing at NASA Lewis Research Center

(NASA-TM-100241) SPRE 1 FREE-PISTON STIRLING ENGINE TESTING AT NASA LEWIS RESEARCH CENTER (NASA) 15 p Avail: NTIS HC A03/MF A01 CSCL 10B
N88-11747
Unclas
G3/20 0107322

James E. Cairelli
Lewis Research Center
Cleveland, Ohio

Prepared for the
1988 Solar Energy Conference
sponsored by the American Society of Mechanical Engineers
Golden, Colorado, April 10–14, 1988

SPRE I FREE-PISTON STIRLING ENGINE TESTING AT NASA LEWIS RESEARCH CENTER

James E. Cairelli
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

E-3865

Abstract - As part of the NASA funded portion of the SP-100 Advanced Technology Program the Space Power Research Engine (SPRE I) was designed and built to serve as a research tool for evaluation and development of advanced Stirling engine concepts. The SPRE I is designed to produce 12.5 kW electrical power when operated with helium at 15 MPa and with an absolute temperature ratio of two.

The engine is now under test in a new test facility which was designed and built at NASA LeRC specifically to test the SPRE I. This paper describes the SPRE I, the NASA test facility, the initial SPRE I test results, and future SPRE I test plans.

Introduction - As part of the NASA funded portion of the SP-100 Advanced Technology Program the Space Power Research Engine (SPRE I) was designed and built, on contract by Mechanical Technology Inc. (MTI), to serve as a research tool for the evaluation and development of advanced Stirling engine concepts. These include active dynamic balancing, hydrodynamic bearings, heat pipe heat exchangers and power control. The Stirling engine technologies developed in the SPRE I ultimately will be used in nuclear and solar space power systems. The technologies developed in this project also apply directly to solar terrestrial power systems.

A new test facility has been designed and built at NASA Lewis Research Center specifically for testing the SPRE I. The SPRE I has been installed in the NASA test facility and is now under test. The following describes the SPRE I engine, the NASA test facility, initial NASA test results, and future SPRE I test plans.

SPRE I Engine - The SPRE I is a free-piston Stirling engine coupled to a linear alternator to produce electrical power. Two SPRE engines were derived directly from the Space Power Demonstrator Engine (SPDE) which was designed, built, and tested by MTI as a two cylinder opposed engine having a common expansion space (hot end). The SPDE was cut in two and the hot end of the cylinders were modified to close off the cylinders; thus forming two separate engines. The SPRE I was delivered to NASA LeRC. The SPRE II remains at MTI. Additional description of the SPDE and SP-100 Stirling Program may be found in references 1, 2, 3, and 4.

Figure 1 is a photo of the SPRE I as it arrived at NASA. Figure 2 is a later photo showing the SPRE I installed in the NASA test cell.

The SPRE is designed to produce 12-1/2 kW of electrical power with 50 kW thermal power input to the heater while operating at 100 Hz with helium at 15 MPa and an absolute heat exchanger wall temperature ratio, T(heater)/T(cooler), of two. Heat is supplied to the engine by circulating molten salt through the engine heater and waste heat is rejected by circulating water through the engine cooler. For these tests the electrical power produced by the engine is absorbed by a water cooled resistance load.

The SPRE engine is shown in cross section in figure 3. The engine has two moving parts, a power piston and a displacer piston contained in a single cylinder. The displacer separates the hot end of the cylinder from the cold end. The hot end of the cylinder is connected to the cold end through annular type heat exchangers (heater, regenerator, and cooler).

In order to have potential for long life, both the piston and displacer are guided by hydrostatic gas bearings. This eliminates any chance of wear due to contact between the moving parts and stationary parts.

Each piston has its own gas spring. The displacer gas spring is divided into a forward gas spring and an aft gas spring. The weights of the pistons and the spring rates are designed such that the resulting spring-mass systems operate with about an 85 degree phase angle between the piston motions.

The motion of the displacer causes the helium working gas contained in the cylinder to flow through the heat exchangers alternately between the hot end of the cylinder (expansion space) and the cold end of the cylinder (compression space). The working gas temperature alternates between hot and cold, as it flows back and forth through the regenerator, causing a corresponding change in pressure. The power piston motion changes the total volume occupied by the working gas.

The piston and displacer motions are synchronized so that the working gas is compressed by the power piston while the gas is in the cold end of the cylinder and expanded while the gas is in the hot end of the cylinder. The heat energy extracted from the gas during expansion is replenished by the heater and the energy transmitted to the gas during compression is extracted from the gas by the cooler.

The net power produced by the power piston is converted to electrical power by a linear alternator which consists of an alternator plunger, with permanent magnets, attached to the power piston (the armature); and stationary electrical windings and core material attached to the engine case (the stator).

Because the single cylinder engine is not inherently balanced, a large mass (about 2000 kg.) is attached to the hot end of the engine to reduce the maximum case motion to less than 0.1 mm. The engine and mass are separated by a thin walled stainless steel spool piece to minimize axial thermal conduction losses.

The engine instrumentation used for these tests are shown in figure 4. The instrumentation is used to measure steady state surface and gas temperatures; dynamic pressures within the cycle and in each of the gas springs; and piston and displacer dynamic positions. These measurements are used to analyze the engine's thermodynamic cycle and to evaluate thermal losses.

<u>Salt Heating Systems</u> - The SPRE salt heating system is shown schematically in figure 5. About 2500 kg. of a molten salt mixture of sodium nitrate, sodium nitrite, and potassium nitrate, are contained in an insulated storage tank heated by electric heaters. The salt is pumped through the engine heater and then returns to the tank where it is reheated. An automatic control maintains the salt tank temperature, over a range of 150C to 450C, by regulating the power to the electric heaters. The temperature range can be extended to 540C by changing the salt mixture. The salt flow is maintained at about 1.7 L/sec. by a fixed orifice in the salt return line.

The measurements made in the salt heating system are used to determine the thermal energy input to the engine heater; and to monitor and control the salt temperature.

To avoid exposing the engine to severe thermal shock, steam is used to heat the engine to match the salt temperature before the circulating pump is started.

<u>Cooling Water System</u> - The SPRE cooling water system is shown in figure 6. The engine is cooled by circulating water through the engine cooler. The pressure vessel surrounding the alternator, and several electrical load components are also water cooled. Automatic controls are used to maintain constant total water flow and inlet temperature to the engine. The flow control range is from 0.5 to 1.5 L/sec. The temperature control is adjustable from about 20 to 80C.

The cooling water system is instrumented to measure the heat rejected by the engine cooler, alternator cooler, and the electrical load; for flow and temperature control; and to monitor the system.

<u>Helium System</u> - Figure 7 is a simplified schematic of the helium system. The system consists of a helium bottle supply, mean pressure control with an operating range of 5 to 15 MPa to charge the engine with working gas, a control to center the displacer stroke for starting, and circulating pumps for the displacer and power piston hydrostatic bearings. Displacer centering is accomplished by adding gas to or venting gas from the aft displacer spring. An emergency stop valve is also included to stop the displacer motion by connecting the displacer forward and aft gas spring volumes together.

Instrumentation is provided to monitor the engine mean pressure and gas bearing circulation circuits.

<u>Electrical Load System</u> - In order to absorb the electrical power produced by the alternator and to control the power piston stroke, an electrical load system is included in the test setup. Figure 8 is a simplified schematic drawing of the electrical load system. The load system contains an a.c. circuit comprised of the alternator in series with manually selected tuning capacitors and an unfiltered d.c. circuit made up of a full-wave rectifier, 16 selectable fixed resistors, and two transistor regulated variable resistors.

Since the alternator voltage and resultant d.c. voltage is directly proportional to the piston stroke, the power piston stroke control is accomplished by using an automatic voltage control which selects the proper number of fixed resistors and amount of variable resistance to maintain the desired d.c. voltage. The normal piston amplitude (half stroke) control range is from 5 mm to 10 mm.

A variable transformer connected to the 60 Hz a.c. commercial line power and tied to the load system through a pair of relay contacts is used to start the engine. This arrangement provides a precise and convenient way to control piston stroke while the load system is being brought "on line". During starting the contacts are closed and the voltage adjusted to drive the alternator/piston. After the engine has started, the load control is adjusted, slowly, to absorb all of the alternator electrical output. At this point, the contacts are opened to isolate the starting power source from the load system. This procedure provides an absolutely "bumpless" transfer from the starting system to the load control system.

The load system instrumentation include alernator voltage and current, load voltage, and tuning capacitor voltage. These dynamic measurements are used to analyze the alternator and load characteristics. In addition, alternator, load, and starting power are measured.

Safety Systems - In order to protect the engine from damage due to hardware malfunction or operator error, several engine and facility operating parameters are continuously monitored. These include piston and displacer positions, bearing differential pressures, cooling water flow, and engine case acceleration. If any of these parameters are out of preset limits, engine shutdown is initiated automatically by opening the displacer spring short circuit valve and connecting all resistors into the alternator load (a pseudo electrical short circuit). This shutdown procedure has been demonstrated to be smooth , well controlled, and with no risk to the engine; even at maximum power condition.

Data Acquisition - Steady state measurements (up to 256 data channels) are monitored and, upon request, are recorded using a central data system known as ESCORT. The dynamic measurements are recorded and processed by a dedicated personal computer (PC) using fast Fourier analysis. Processed data results are displayed on the PC's CRT display and are transmitted by computer link into ESCORT where they are merged with the steady state data. To aid in running the test, a limited number of "on line" calculations are made by ESCORT. The results of these calculations and all data input to ESCORT, including PC data, can be viewed on two ESCORT CRT displays. Upon command, hard copies of the ESCORT displays can be made on a local printer. Data recorded by ESCORT is transmitted to a data base file in the central computer for further batch processing, after the test.

Test Results - At this time only about 35 hours of SPRE I testing has been done, at NASA,; primarily to check out the facility systems and to verify the accuracy of the data. This process is still under way. The engine has been operated at temperature ratios of 1.6, 1.8, and 2.0, mean pressures of 5.0, 7.5, 10.0, 12.5, and 15 MPa; and piston amplitudes of 5.0, 6.0, 7.0, 8.0, and 9.0 mm. The following is a sampling of the data taken to date at a temperature ratio of two.

Figure 9 shows the measured piston P-V power versus the piston stroke at the various pressures. The maximum P-V power measured was 11.80 kW. The P-V power tends to vary linearly with both the piston amplitude and the mean pressure.

The measured alternator power is shown in figure 10. The maximum alternator power measured was 7.47 kW. The trends of alternator power are similar to those of the P-V power. The alternator power varies linearly with piston amplitude. However, the relation to mean pressure appears to be more complex.

Figure 11 shows the relation of displacer amplitude to piston amplitude at various pressures. The displacer amplitude tends to vary linearly with piston amplitude and appears to increase with increasing pressure by a constant which is a function of the mean pressure.

The phase angle of the displacer motion relative to to piston motion is shown in figure 12. The displacer phase angle varies from about 84 degrees to 89 degrees. The angle appears to decrease slightly (about two degrees) with increasing piston amplitude for a constant pressure. For each different pressure, the phase angle appears to shift by a constant angle which is a function of the pressure.

Figure 13 shows the relation of engine frequency to mean pressure. The predicted frequency is also shown for reference. The measured frequency appears to be about 2 to 3 Hz higher than the predicted value.

SPRE Test Plans - SPRE baseline performance will be measured following completion of facility check out. Baseline performance tests will be repeated with a dynamic balancer installed to replace the 2000 kg mass. Testing will then turn to component development primarily to evaluate the use of hydrodynamic displacer bearings and alternate regenerator materials. Throughout the SPRE testing there will be an effort made to gather appropriate engine data for comparison to the NASA computer code predictions and to improve the code to better predict engine performance. We plan to present the results of these activities in future NASA reports.

References -

1. 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.

2. Slaby, J. G., "Overview of the 1985 NASA Lewis Research Center SP-100 Free-Piston Stirling Engine Activities", NASA TM-87028, 1985.

3. Slaby, J. G., "Overview of Free-Piston Stirling SP-100 Activities at the NASA Lewis Research Center", NASA TM-87156, 1985.

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

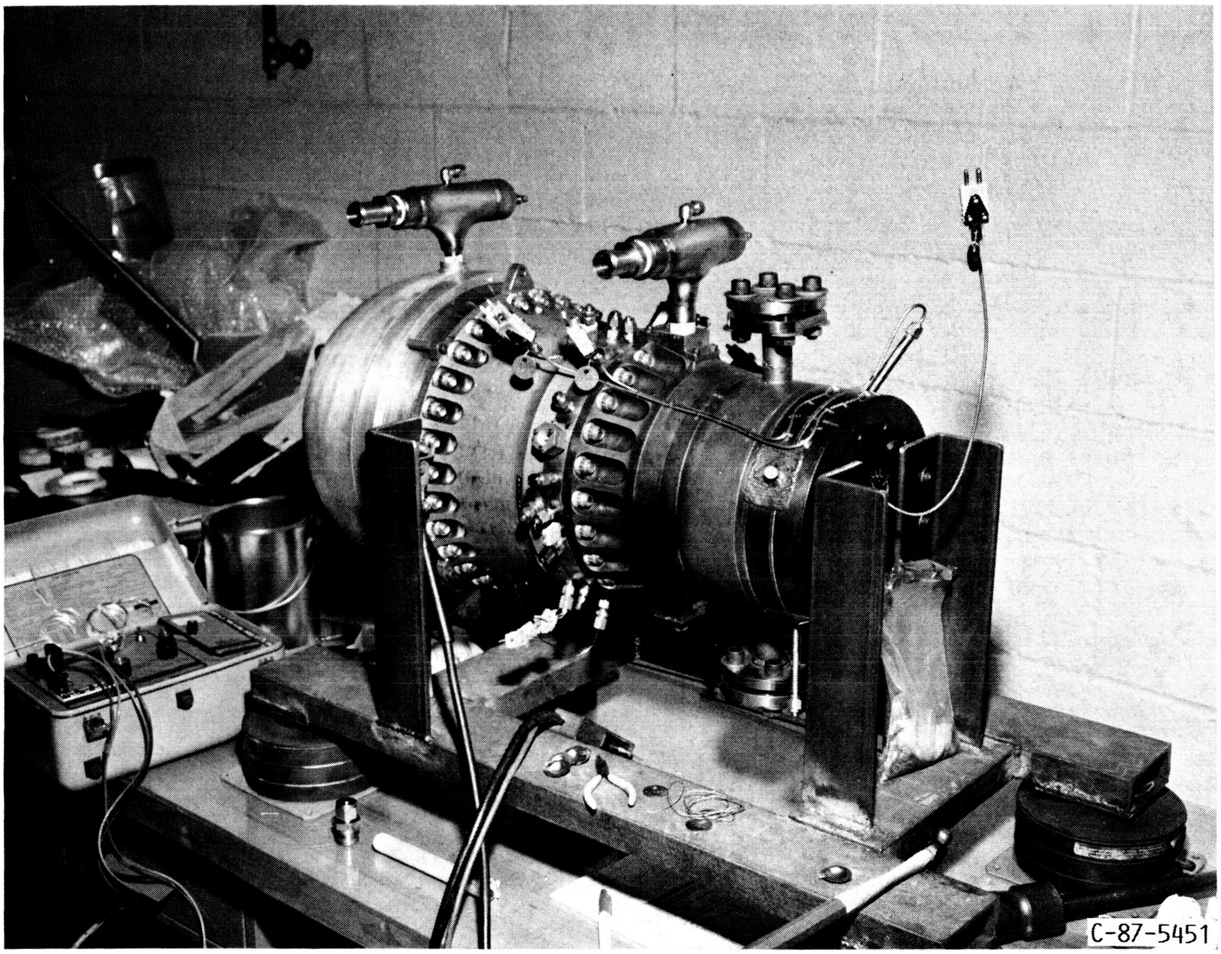

FIGURE 1. - SPRE I AS RECEIVED AT NASA.

ORIGINAL PAGE IS
OF POOR QUALITY

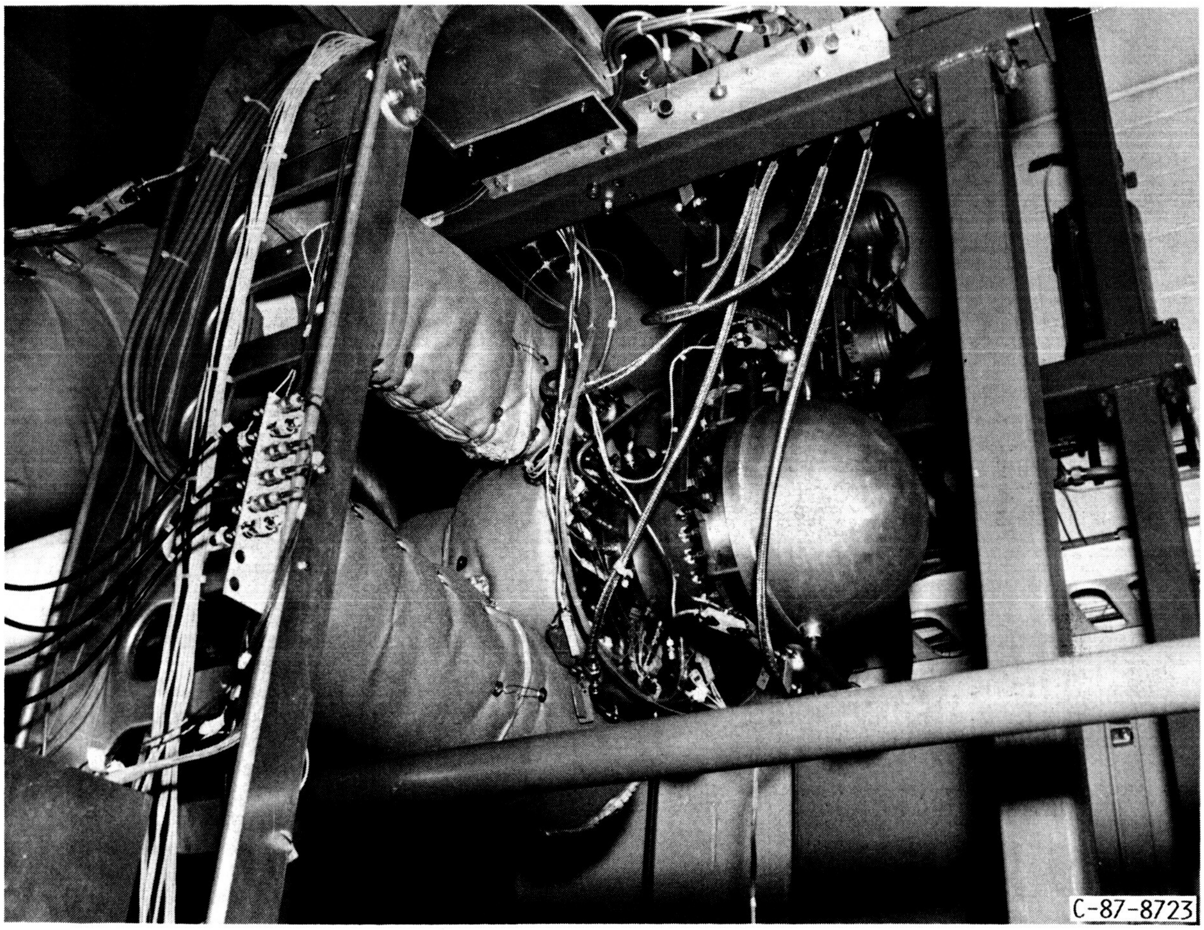

FIGURE 2. - SPRE I INSTALLED IN THE NASA FACILITY.

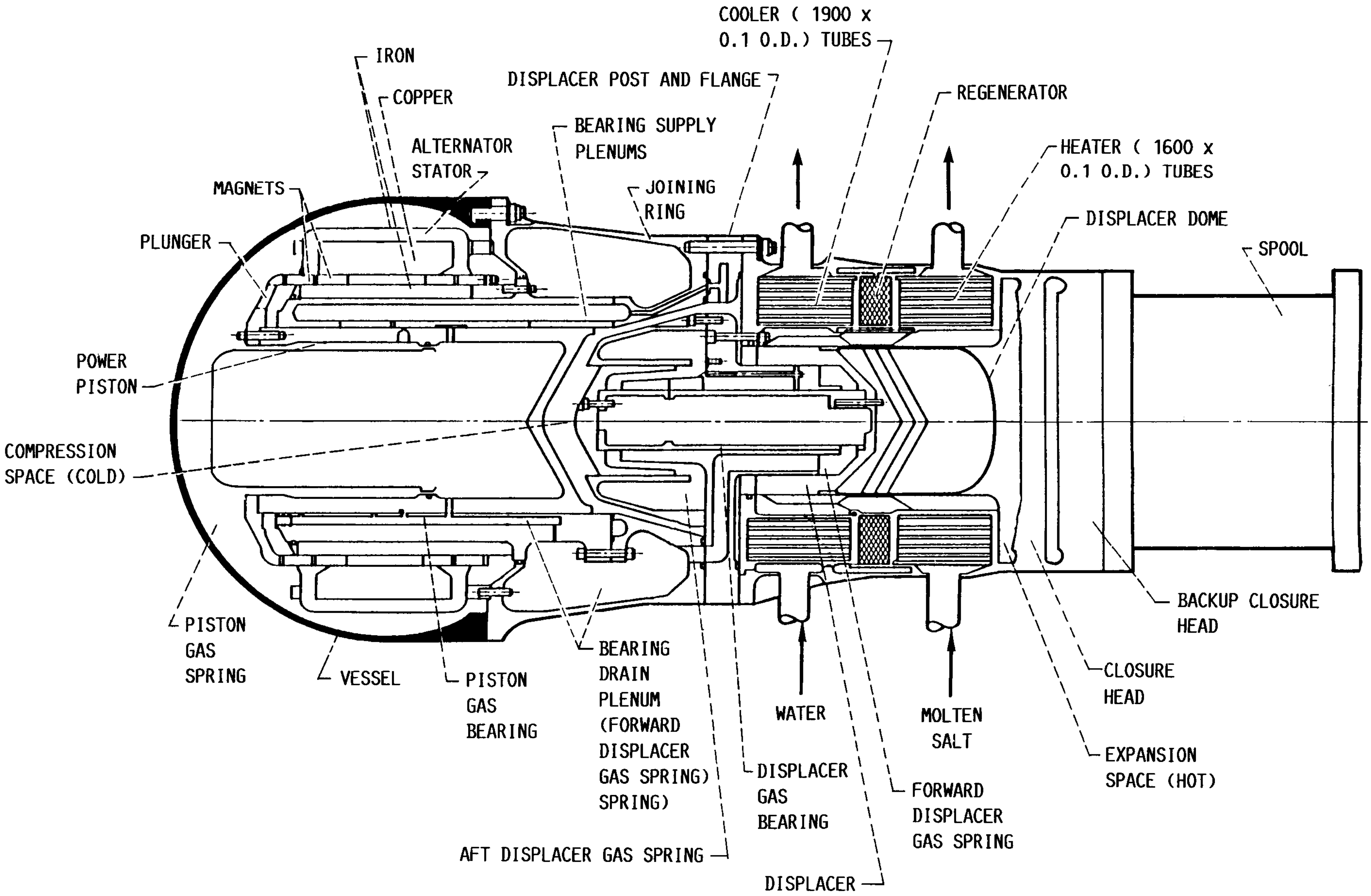

FIGURE 3. - SPRE CROSS SECTION.

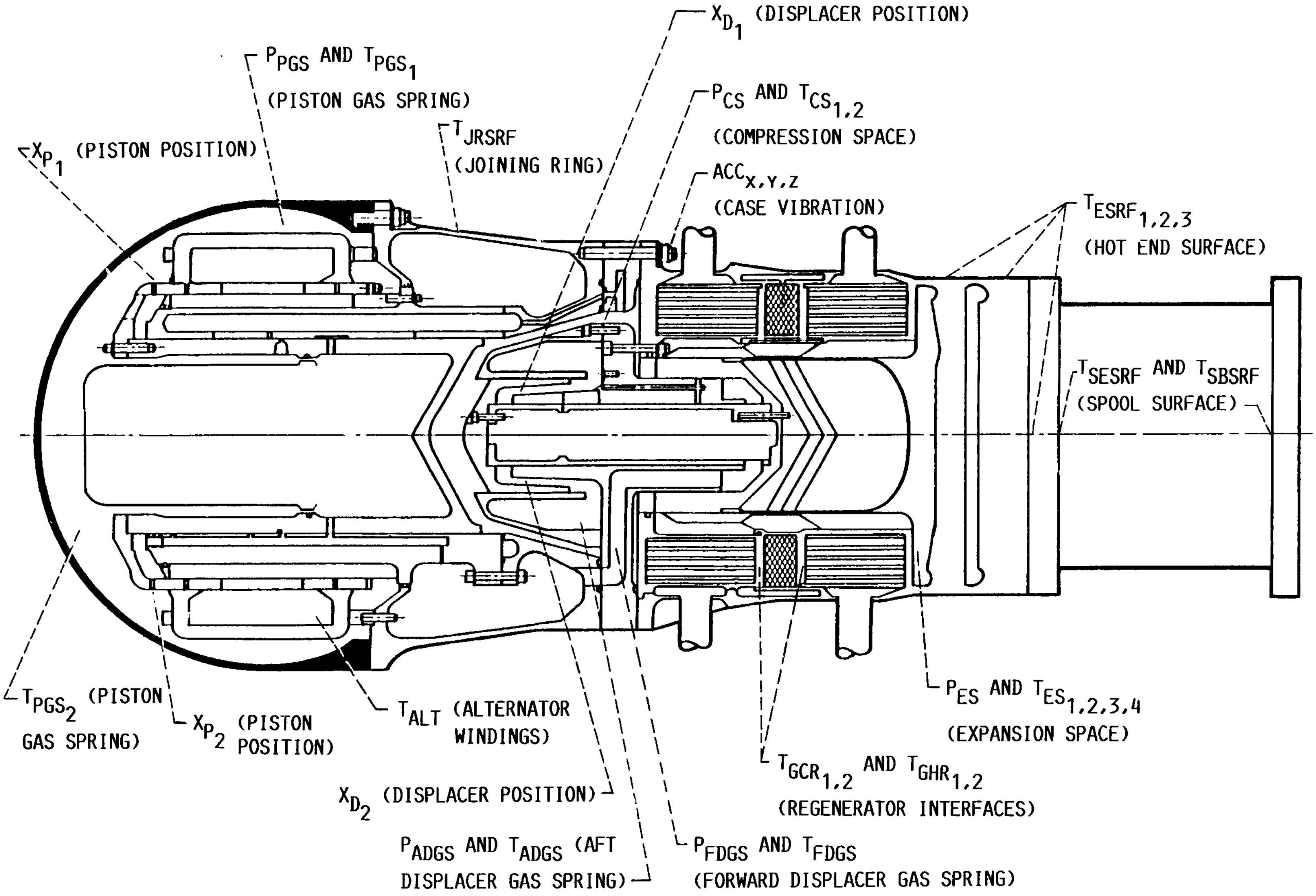

FIGURE 4. - SPRE INSTRUMENTATION.

FM	FLOWMETER
P	PRESSURE TRANSDUCER
PR	PRESSURE REGULATOR
T/C	THERMOCOUPLE
ΔP	PRESSURE TRANSDUCER DIFFERENTIAL
ΔT	DIFFERENTIAL TEMPERATURE

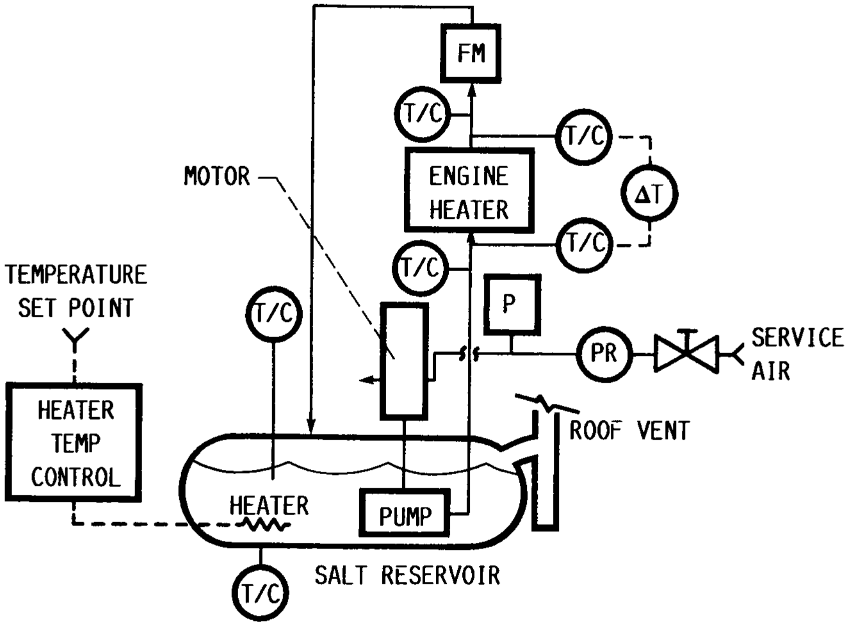

FIGURE 5. - SALT HEATING SYSTEM.

FM	FLOWMETER
P	PRESSURE TRANSDUCER
PR	PRESSURE REGULATOR
T/C	THERMOCOUPLE
ΔP	PRESSURE TRANSDUCER DIFFERENTIAL
ΔT	DIFFERENTIAL TEMPERATURE

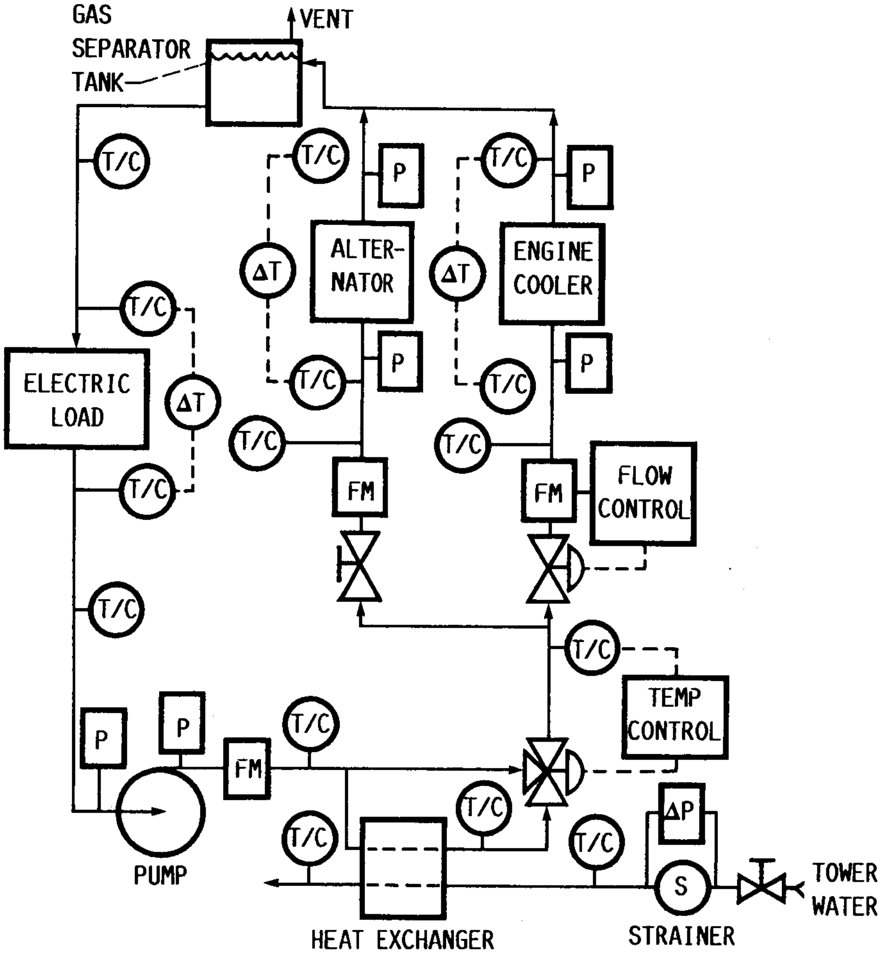

FIGURE 6. - COOLING WATER SYSTEM.

FM	FLOWMETER
P	PRESSURE TRANSDUCER
PR	PRESSURE REGULATOR
T/C	THERMOCOUPLE
ΔP	PRESSURE TRANSDUCER DIFFERENTIAL
ΔT	DIFFERENTIAL TEMPERATURE

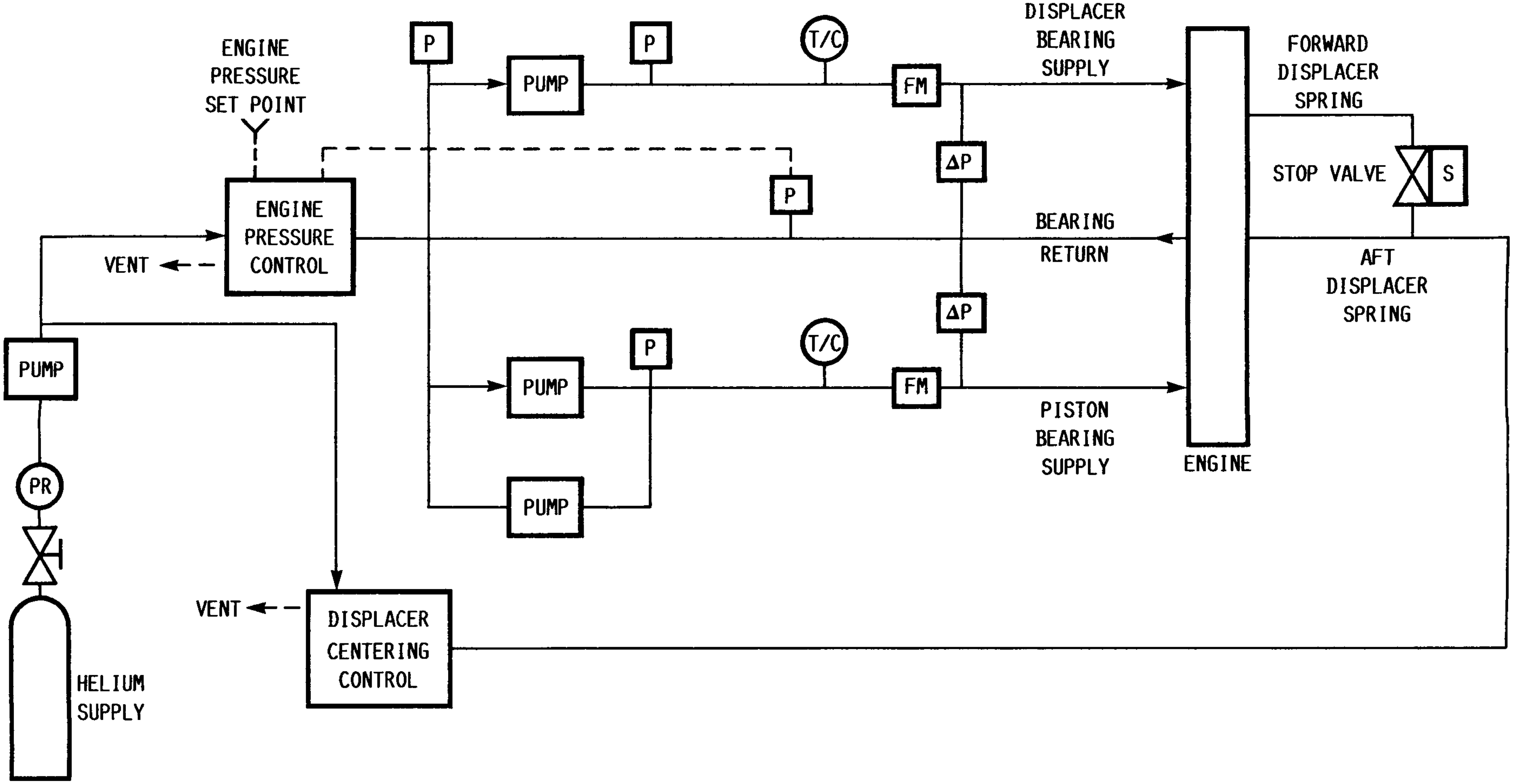

FIGURE 7. - HELIUM SYSTEM.

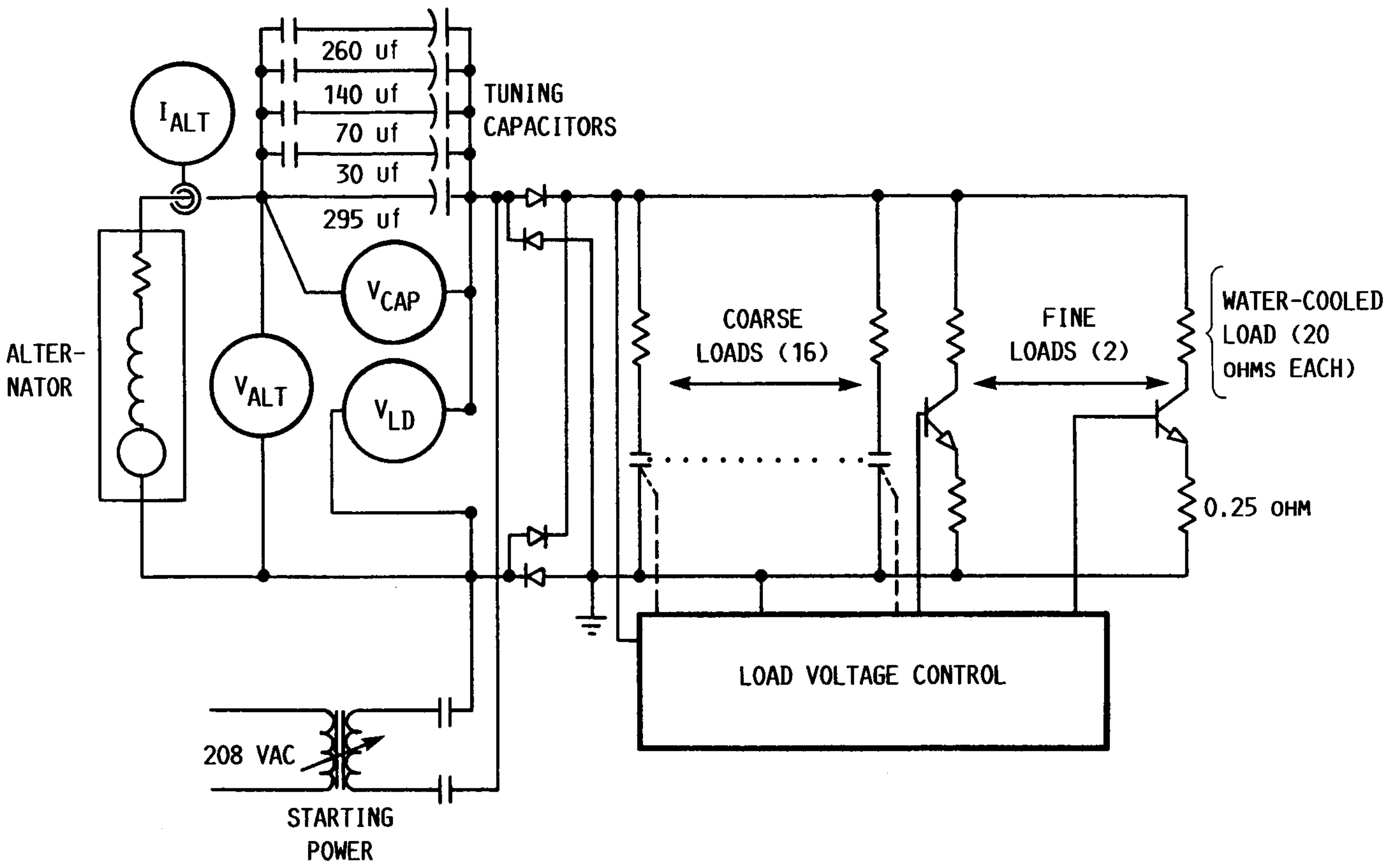

FIGURE 8. - ELECTRICAL LOAD SYSTEM.

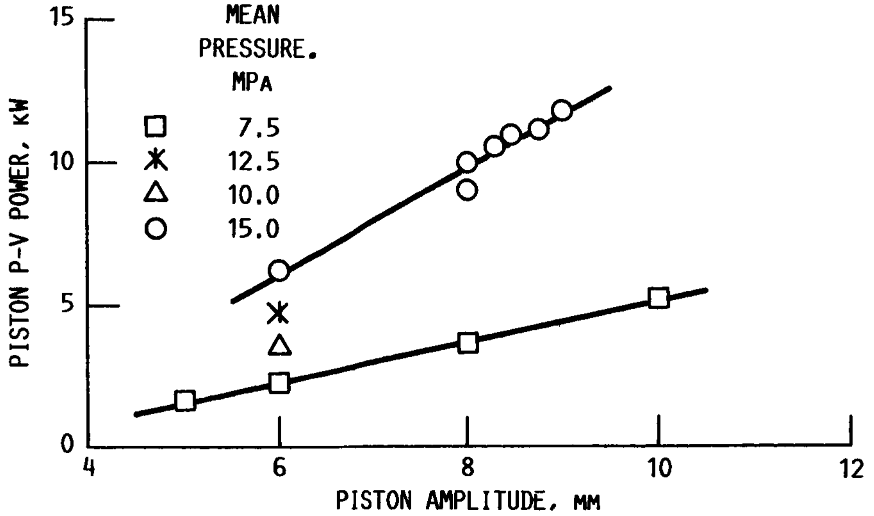

FIGURE 9. - PISTON P-V POWER VERSUS PISTON AMPLITUDE.

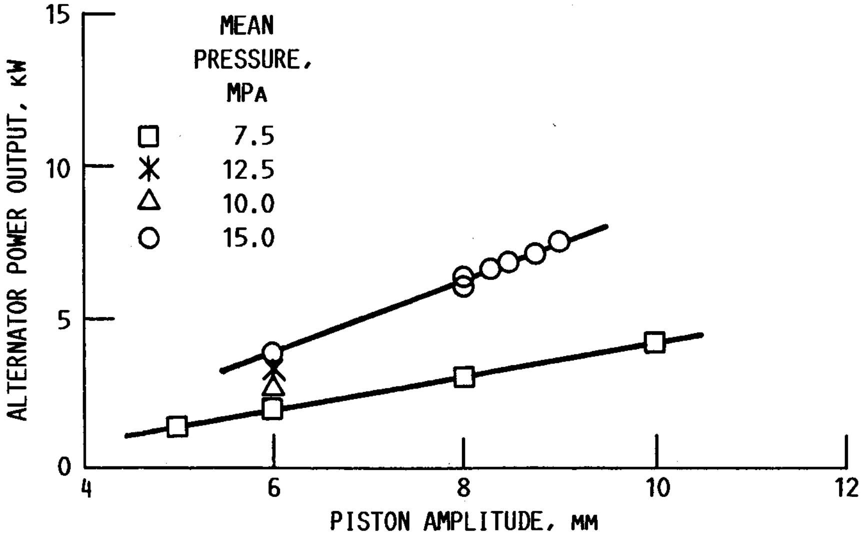

FIGURE 10. - ALTERNATOR POWER VERSUS PISTON AMPLITUDE.

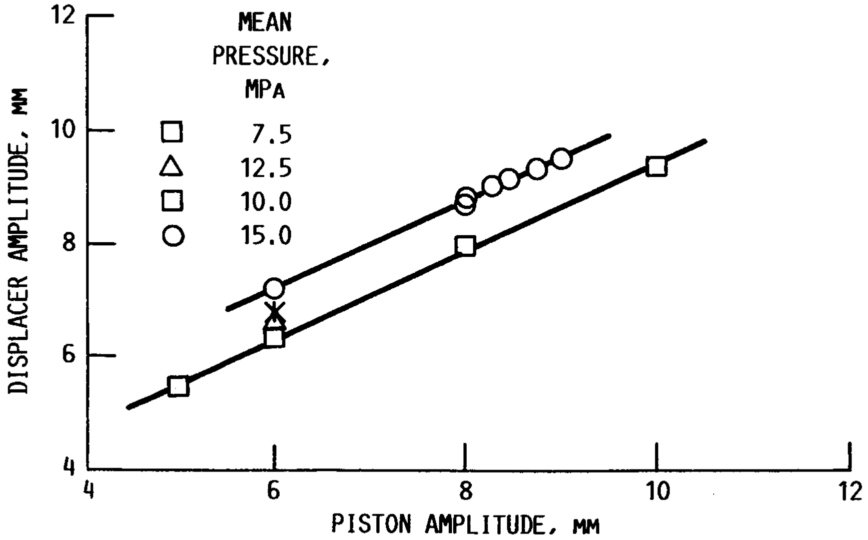

FIGURE 11. - DISPLACER AMPLITUDE VERSUS PISTON AMPLITUDE.

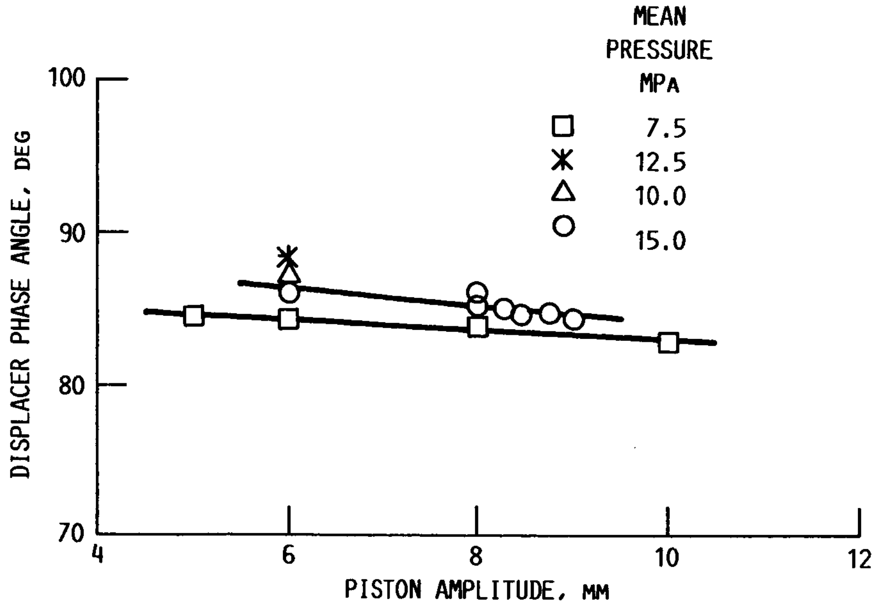

FIGURE 12. - DISPLACER PHASE ANGLE VERSUS PISTON AMPLITUDE.

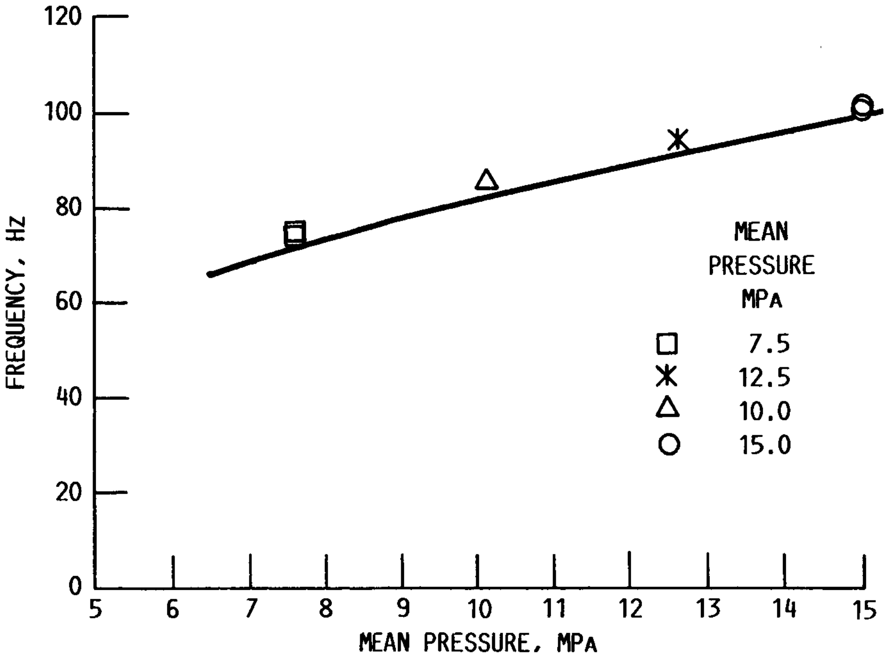

FIGURE 13. - FREQUENCY VERSUS MEAN PRESSURE.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-100241	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle SPRE I Free-Piston Stirling Engine Testing at NASA Lewis Research Center		5. Report Date
		6. Performing Organization Code
7. Author(s) James E. Cairelli		8. Performing Organization Report No. E-3865
		10. Work Unit No. 506-41-31
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 1988 Solar Energy Conference sponsored by the American Society of Mechanical Engineers, Golden, Colorado, April 10-14, 1988.

16. Abstract

As part of the NASA funded portion of the SP-100 Advanced Technology Program the Space Power Research Engine (SPRE I) was designed and built to serve as a research tool for evaluation and development of advanced Stirling engine concepts. The SPRE I is designed to produce 12.5 kW electrical power when operated with helium at 15 MPa and with an absolute temperature ratio of two. The engine is now under test in a new test facility which was designed and built at NASA Lewis specifically to test the SPRE I. This paper describes the SPRE I, the NASA test facility, the initial SPRE I test results, and future SPRE I test plans.

17. Key Words (Suggested by Author(s)) Free-piston Stirling Test data Test facility Space power	18. Distribution Statement Unclassified - Unlimited Subject Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No of pages	22. Price*
Unclassified	Unclassified	14	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161