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Component Technology for Stirling Power Converters

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NASA

COMPONENT TECHNOLOGY FOR STIRLING POWER CONVERTERS

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ABSTRACT

NASA Lewis Research Center has organized a component technology program as part of the efforts to develop Stirling converter technology for space power applications. The Stirling space power program is part of the NASA High Capacity Power Project of the Civil Space Technology Initiative (CSTI). NASA Lewis is also providing technical management for a DOE/Sandia program to develop Stirling converters for solar terrestrial power producing electricity for the utility grid. The primary contractors for the space power and solar terrestrial programs develop component technologies directly related to their program goals. This Lewis component technology effort, while coordinated with the main programs, aims at longer term issues, advanced technologies, and independent assessments. This paper will present an overview of work on linear alternators, engine/alternator/load interactions and controls, heat exchangers, materials, life and reliability, and bearings.

INTRODUCTION

Stirling technology development for space power applications is funded under the NASA Civil Space Technology Initiative (CSTI). The objective of the CSTI High Capacity Power element is to develop the technology base needed to meet the long duration, high capacity power requirements for future NASA space initiatives.

The primary goal for the current Stirling space power effort is the development of a 25 kWe/cylinder Stirling converter operating at a hot-end temperature of 1050 K and a temperature ratio (hot-end temperature/cold-end temperature) of 2.0. The lifetime requirement is 60 000 hr. This work is being done under contract to Mechanical Technology, Inc. (MTI). The converter now being built under this contract is the 12.5-kWe/cylinder Component Test Power Converter (CTPC); this converter will have a limited lifetime (hot-end material will be Inconel 718) and will be used to develop the technologies needed to meet the final goals of the contract. Following the CTPC, a 25-kWe/cylinder converter, the Stirling Space Power Converter (SSPC) will be designed and fabricated; as currently planned, it will use Udimet 720 as the hot-end material to meet the creep-strength requirements for the 60 000 hr life. This program is discussed in [1]. A schematic of the Stirling power converter is shown in figure 1. The final objective of the NASA Stirling space power program is a Stirling converter operating at a 1300 K hot-end temperature to fully utilize the capability of the SP-100 reactor.

The Advanced Stirling Conversion System (ASCS) solar terrestrial program is discussed in [2]. The design requirements for the ASCS include a 25-kWe output, a Stirling hot-end temperature of 973 K, and a lifetime of 60 000 hr. The primary contractors in this program are Stirling Technology Company (STC) and Cummins Engine Company.

The NASA Lewis component technology program is coordinated with the primary space power and solar terrestrial efforts but is aimed at longer term issues, advanced technologies, and independent assessments of technology issues. The objectives of the Lewis component technology program are as follows:

(1) To evaluate alternate approaches to the critical technologies of the primary converter designs.

(2) To augment the component technology work for the primary converter designs.

(3) To evaluate advanced concepts for future design improvements.

(4) To enhance NASA Lewis' expertise and understanding of technology issues.

The component technology program is coordinated by the Stirling Technology Branch of the Power Technology Division and is conducted through in-house and contracted programs utilizing industry, universities, NASA Lewis research and matrix organizations, and other government agencies.

LINEAR ALTERNATORS

Linear Alternator Test Rig

A linear alternator test rig is being developed to provide both static and oscillating alternator test capabilities. The main objective for the test rig is to evaluate advanced linear alternator concepts aimed at decreasing alternator specific mass, increasing high temperature life and reliability, and increasing alternator efficiency.

For current Stirling space power converter designs, the linear alternator represents about 1/3 of the mass of the converter. For a SP-100 nuclear Stirling lunar base, the power converter mass varies from about 20 percent (for a 100-kWe power system) to about 30 percent (for a 750-kWe power system) of the total power system mass. Thus, the linear alternators represent about 7 to 10 percent of the total power system mass. Reducing linear alternator mass while maintaining or increasing efficiency has significant potential for reducing total power system mass.

Both linear alternator specific mass and efficiency affect the total power system mass. Tradeoff studies for a SP-100 nuclear Stirling lunar base indicate that a 1 kg/kWe reduction in power converter specific mass (at constant converter efficiency) yields about the same reduction in total system mass as does a gain of 2½ to 3 percentage points in converter efficiency (at constant converter specific mass). Note that a 5 percentage point gain in linear alternator efficiency gives about a 1½ percentage point gain in converter efficiency. The specific mass of current permanent magnet linear alternators for space power applications is about 2.3 kg/kWe; the efficiency is approximately 88 percent.

A further primary goal for the advanced linear alternators is reliable high temperature operation for a 60 000 hr lifetime. Nuclear power system designs using Stirling converters with hot-end temperatures of 1050 K optimize for minimum mass at converter temperature ratios around 2.0. Thus, the cold end of the power converter including the region of the linear alternator operates at temperatures around 525 K. This operating temperature and the lifetime are severe requirements for permanent magnet linear alternator designs.

The in-house design of the test rig is nearing completion. The test rig requirements include sinusoidal reciprocating motion, frequencies up to 120 Hz, strokes up to 40 mm, and eventual testing at temperatures up to 575 K. Initial operation will utilize an existing 1.5 kW linear driver and should allow testing of test alternators with outputs of 1 kWe. The existing linear driver may be upgraded to a higher power driver (3 to 5 kW) at some point in the future. Maximum frequency and maximum stroke cannot be obtained at the same time due to fatigue and endurance limits for the reciprocating parts and also rig loss limitations. The rig will allow testing at stroke-frequency combinations that are used in current space power converter designs, including the Space Power Demonstrator Engine (SPDE) and the CTPC.

The test rig layout is shown in figure 2. A double-acting gas spring balances the inertia forces of the moving components. The linear driver, test alternator, moving components, and gas spring inner cylinder are placed inside of a pressure vessel. The mean pressure of the test rig minimizes leakage from the gas spring. The inner cylinder has a thick wall to minimize deflections and, thus, aid in maintaining the clearance seal of the gas spring piston. This test rig layout does sacrifice some accessability to the test alternator but a large space was left around the test alternator inside the pressure vessel to reduce this impact. The clearance around the test alternator was also desirable to eliminate flux leakage effects to the pressure vessel.

Linear Alternator Analysis

NASA Lewis is assembling a design and evaluation tool for inhouse linear alternator analysis. It will be based on conventional magnetic field mapping and conventional magnetic circuitry approximations and assumptions. This analysis will provide first-cut alternator designs and performance evaluations; it will also be used to screen alternator designs prior to using a more advanced analysis technique.

NASA Lewis has a contract with Hollidaylabs to develop advanced analysis procedures for linear alternators. Most nonproprietary linear alternator analysis techniques either neglect certain complex magnetic flux leakage effects or treat them on an empirical basis. The empirical factors are based on test data. It is difficult through testing to separate out related physical phenomena so, often, only overall effects can be determined. Also, these leakage effects are strongly dependent on the linear alternator geometry; thus, defining these parameters empirically limits the general application of the technique due to difficulties in extrapolating to other geometries. This analysis effort is aimed at developing techniques that allow an accurate evaluation of a broad general class of permanent magnet linear alternators without relying on empirical relations.

The advanced analysis techniques will include the mathematical evaluation of configuration dependent parameters, complex leakage fields, eddy braking phenomena, and the effects of the surrounding support structure. An advanced finite element analysis computer program, ANSYS, is being used for the evaluation of the complex leakage fields. At this time, the analysis is two dimensional and axisymmetric; it could possibly be extended to three dimensions and could then be used to analyze such issues as lamination stacking techniques. To aid in verifying the procedures of the advanced analysis technique, two permanent magnet linear alternator designs will be compared and evaluated.

Permanent Magnet Properties

A test facility has been developed at NASA Lewis to determine the effects on rare-earth permanent magnets of short and long term exposures to elevated temperatures. To date, 10 samples of Sm_2Co_{17} from each of five vendors have been tested to 575 K to investigate short-term temperature effects. Results from these tests are reported in [3]. The magnetics test fixture is shown in figure 3. Future testing will evaluate magnet aging effects due to long term exposure to these temperatures.

ENGINE/ALTERNATOR/LOAD INTERACTIONS AND CONTROLS

A program has been initiated to investigate the interactions between the free-piston Stirling engine (FPSE), the linear alternator, the load, and the control system. The objectives are: (1) to experimentally characterize FPSE control approaches; (2) to evaluate the transient response of the power converter and controls to various load transients; and (3) to characterize control approaches for systems with multiple power converters. Analytical models will be developed for both single-converter and multiple-converter systems.

Figure 4 shows a 1-kWe SPIKE free-piston Stirling engine with a linear alternator that has been installed in a NASA Lewis test cell. The SPIKE engine was originally built by Sunpower, Inc.; NASA Lewis has obtained several of these engines that were built under previous government programs. Checkout tests of the SPIKE engine have been started.

It is planned to test over a wide range of steady state and transient conditions with various ac and dc loads to develop the load control for a single-converter system. The system response to motor loads will be of particular interest. Then, a multiple-converter system will be simulated using the single SPIKE engine and simulating other engine/alternators with an electrical power supply; this will be used to evaluate control approaches for multiple-converter systems. At some point, one or more additional engines will be added to demonstrate the operation of a multiple-converter system.

HEAT EXCHANGERS

Regenerator Heat Transfer Testing

Under Phases I and II SBIR programs for NASA Lewis, Sunpower, Inc. designed and fabricated both oscillating flow and steady flow test rigs to measure oscillating flow pressure drop in Stirling engine heat exchangers. These rigs are described in [4]. This program has been successfully completed. Under another Phase I SBIR, Sunpower modified the oscillating flow test rig to allow the measurement of regenerator heat transfer; data reduction procedures for determining the heat transfer coefficient and an enhanced axial conductivity factor were also developed.

Both test rigs have now been loaned to Ohio University for use in their Center for Stirling Technology Research (CSTR). CSTR has installed the oscillating flow test rig in their facilities for use in measuring regenerator heat transfer in oscillating flow. They intend to operate the test facility for the research and development needs of NASA, other government agencies, corporations, and academic investigators.

The oscillating flow test rig is shown as installed at Ohio University in figure 5. A schematic of the modifications to the rig for the regenerator heat transfer testing is shown in figure 6. A frequency capability of 120 Hz and a mean pressure up to 15 MPa allows for testing at flow conditions found in most Stirling engines.

Anisotropic Composite Regenerator

Energy Science Laboratories, Inc. (ESLI) has received a Phase II SBIR to develop an advanced concept Stirling regenerator. This composite regenerator's anisotropic properties offer performance advantages that cannot be obtained with conventional homogenous materials. The regenerator uses high thermal conductivity fibers (to provide enhanced conduction transverse to the flow path) layered within a matrix material that has a high heat capacity and a low thermal conductivity (for reduced axial conduction). Material choices include high-k graphite fibers layered in ceramic and carbon matrices. A schematic of a composite regenerator is shown in figure 7.

These properties should allow a regenerator with increased passage size giving reduced pressure drop while maintaining high thermal efficiency and reducing axial conductivity losses; this should yield an improved converter efficiency. Also, the decreased pressure drop for the same thermal efficiency would allow a longer regenerator with less frontal area. The longer length would reduce thermal stresses in the regenerator wall which is normally the highest stress area in the converter. Converter mass may also decrease due to a reduced overall diameter (less frontal area required in the regenerator) and a thinner regenerator wall due to the reduced stress. In addition, the reduced regenerator stress would allow the current power converter concepts using an annular regenerator to be scaled to higher power levels. Overall, the designer would have more design flexibility to achieve his goals.

This Phase II program is just getting underway. Tasks will include evaluating fabrication alternatives, testing sample regenerators for thermal effectiveness and pressure drop, modeling composite regenerator performance and incorporating this modeling into a Stirling engine simulation, and testing of a composite regenerator in a Stirling engine.

HP-1000 Testing

The HP-1000 engine that is being tested at NASA Lewis is described in [5]. The HP-1000 is a RE-1000 engine that has been modified with a heater head using modular heat exchangers and integral heat pipes. The three heat exchanger modules can be seen in figure 8. Heat input to the working fluid is through a sodium heat pipe integral to each module; the heat pipe evaporators are heated with resistance heaters. The working fluid flows in slots around the periphery of each heater and cooler. Each module also contains an annular regenerator.

The main objectives of the HP-1000 testing are to demonstrate and evaluate the operation of a Stirling engine with heat pipe heat input and to evaluate the modular heat exchanger concept. A variation of these slotted modular heat exchangers is being used on the CTPC cooler; they allow a significant reduction in the number of joints compared to a conventional tube and shell heat exchanger. A sodium heat pipe is also used on the CTPC although of a different design.

Figure 9 shows a comparison of recent HP-1000 test data to GLIMPS computer predictions. Note that the figure compares brake power for the test data to PV power from GLIMPS. Reliable PV power measurements were not obtained during these tests. Based on previous RE-1000 data, the difference between PV power and brake power is about 5 to 8 percent. Accounting for this difference would bring the comparisons to within a few percent. This figure does indicate that the heat pipes and heat exchanger modules have delivered the expected performance for the HP-1000. To date, testing has been done with the heat pipe evaporator oriented at the top of the module; testing will also be done in the reverse configuration (heat pipe evaporator down) to see the effect of any excess liquid sodium collecting in the heat pipe at the heater/regenerator interface.

MATERIALS

Material Creep and Corrosion in Liquid Metal Heat Pipes

The NASA Lewis Materials Division has started an effort to characterize creep and corrosion in nickel-based superalloys operating in a heat pipe environment. The starfish heater head for the SSPC is expected to be made from a high-strength superalloy, Udimet 720, and will be exposed to sodium condensing on its outer surface (a sodium heat pipe is used to transport heat to the Stirling working fluid). The effects of liquid metals on these high-strength superalloy materials is not well-known.

The first tests will be made on Inconel 718 heat pipes operating under an externally applied load. Eventually, tests will also be done on Udimet 720. Nickel transport is one of the main concerns in these tests. Because of their similar nickel content, it is felt that the Inconel 718 samples will give a good indication of any major problems that may be encountered with the Udimet 720. Inconel 718 is a more easily fabricated material which allows tests to be initiated more readily.

NASA Lewis is currently building the first set of heat pipes. The tests will be run at the Energy Technology Engineering Center (ETEC). Testing will be done at a temperature of 1050 K and a heat flux of 20 W/cm^2. Initial tests will be 1000 hr in duration with at least one 10000 hr test to be run in the future. Creep measurements will be made during the tests with corrosion analysis being done at the end of each test.

A key factor in decreasing corrosion in the heat pipes is maintaining a low oxygen level in the pipe. Earlier tests in the CTPC program had indicated that oxygen levels could reach values that were much higher than expected. Since then, new cleaning and filling procedures for the sodium heat pipes have been determined by NASA, ETEC, MTI, and Thermacore. These procedures will be used for preparing samples for the creep and corrosion tests as well as for the starfish fabrication in the space power program. The goal is to keep the starting oxygen level below about 10 ppm.

Joining High-Strength Superalloys

High-strength superalloys such as Udimet 720 cannot generally be joined by conventional fusion welding methods due to cracking problems. Since the high creep strength of Udimet 720 is needed to achieve the 60 000 hr life for the SSPC, suitable joining methods must be determined. Possible methods for joining of the Udimet 720 to itself and to Inconel 718 (used in adjoining parts of the converter) include diffusion bonding, diffusion brazing, inertia welding, and furnace brazing.

An effort is underway with Allied-Signal Aerospace Company, Garrett Fluid Systems Division, to address technology problems associated with the high-strength superalloy materials and their application to free-piston Stirling converters. Their main focus is on joining technology for the Udimet 720. They will review possible joining methods for each Udimet 720 joint; these include the main hot-end joint between the two halves of the converter, transition joints to the Inconel 718 material used in the colder parts of the converter, and a joint to the sodium heat pipe containment vessel. One joint will be selected to define a transient liquid phase diffusion bonding (TLPDB) process. This process can achieve a high-strength bond joint with a hermetic seal and minimal distortion. It is basically a combination of brazing and solid-state diffusion bonding. The TLPDB process is discussed in [6].

Allied-Signal will also review liquid metal compatibility issues for each of the power converter's three liquid metal systems. These are a lithium pumped loop connecting the heat source to the Stirling converter, the sodium heat pipe that provides the heat input to the Stirling working fluid, and a NaK pumped loop that removes the rejected heat from the converter and transports it to the radiator.

LIFE AND RELIABILITY

Life Assessment of Stirling Heater Heads

The NASA Lewis Structures Division has initiated a program to conduct a structural and life assessment analysis of the Udimet 720 starfish heater of the Stirling power converter. The starfish heater is a geometrically complex structural component which transfers heat from the sodium heat pipe to the helium working fluid of the power converter. It is comprised of 50 fins, each containing 28 thin-walled gas passages. The thin walls of the gas passages are under a biaxial stress state due to the high operating pressures of the converter (15±1.8 MPa). The fins are exposed to condensing sodium at 1050 K which will attack the base metal of the starfish. The requirements leave little room for error in the design analysis and fabrication of the starfish heater.

The structural long-term durability of the starfish cannot be properly analyzed with a typical time-independent elastic analysis. The approach to be used in this life assessment is to: (1) provide a high temperature data base for Udimet 720; (2) use this data base to characterize a viscoplastic constitutive model to predict the time-dependent behavior of the Udimet 720; (3) incorporate this viscoplastic model into a three-dimensional, inelastic finite element analysis to provide accurate stress levels and the time-dependent deformation response of the heater head; and (4) develop long-term durability techniques to assess the starfish life.

The test equipment for this effort has been received and testing of the Udimet 720 should begin shortly. A constitutive model has been identified and finite element meshes are being constructed.

A related program is being established to assess the life of the Stirling heater head in the ASCS solar terrestrial program. This heater head is also expected to be made from Udimet 720, has similar pressure and lifetime requirements, and a hot-end temperature of 973 K. The main difference between this application and that for space power is the large number of start-stop cycles for the ASCS causing creep ratchetting concerns. This difference is illustrated in figure 10.

MAGNETIC BEARINGS

The feasibility of magnetic bearings for free-piston Stirling converters is being evaluated by the NASA Lewis Structures Division through a contract with Mechanical Technology, Inc. The potential benefits of magnetic bearings include lower power loss in the bearings, no contact during startup and shutdown, the ability to react to side loads encountered during operation, more design flexibility by allowing separation of the bearing and seal regions, and a possible replacement of the gas springs (with magnetic springs) thus reducing the tight clearance seal requirements.

After a review of various concepts, a four-sector, actively-controlled, all-electromagnetic bearing was selected. The selection criteria included maturity of the design and the technical payoffs (size, weight, and power consumption).

MTI is using a reference design of the SSPC to evaluate the magnetic bearings. They have completed layouts incorporating magnetic bearings on both the power piston and the displacer and also one that includes a magnetic spring for the displacer. It was found that, for reasonable size limitations, the magnetic spring could not provide sufficient stiffness to resonate the displacer; the layout chosen uses both a magnetic spring and a gas spring to provide the required stiffness. Dynamic analysis of the converter with magnetic bearings is now being done. The final task of this contract will be to provide an overall assessment of the advantages and disadvantages of the magnetic bearing concept including its impact on the efficiency, mass, and reliability of the Stirling power converter.

CONCLUDING REMARKS

This paper has provided an overview of the NASA Lewis component technology program that supports the development of the Stirling power converter, primarily for space power applications. The goal of the program is to coordinate with the main power converter development efforts while aiming at longer term issues, advanced technologies, and independent assessments of technology issues. Most of these component technology efforts are just getting underway. It is expected that the results will help guide the development of a long-life Stirling power converter and help meet the goals of high efficiency, low specific mass, and high reliability.

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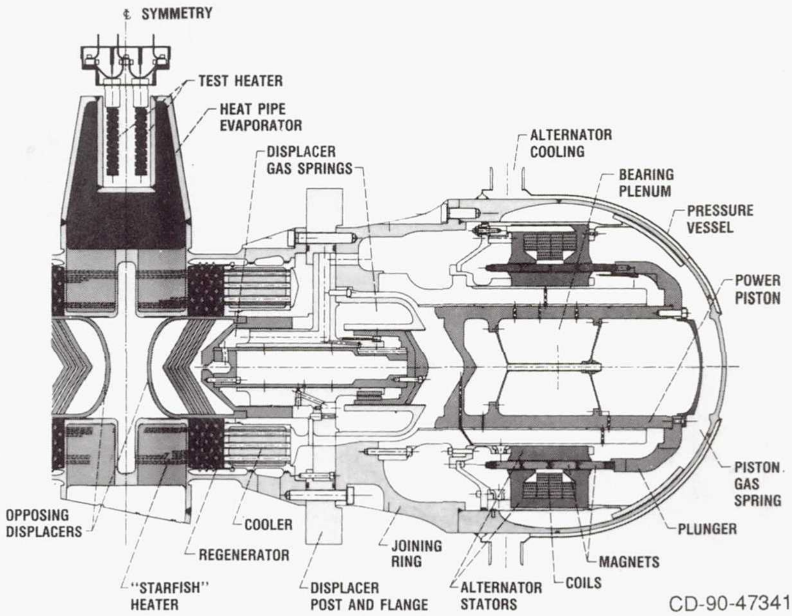

Figure 1.—Stirling power converter.

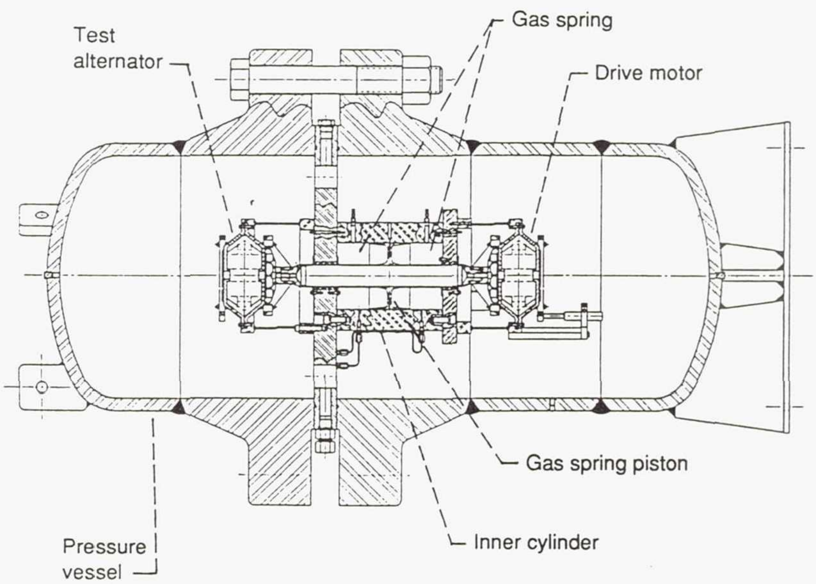

Figure 2.—Linear alternator test rig.

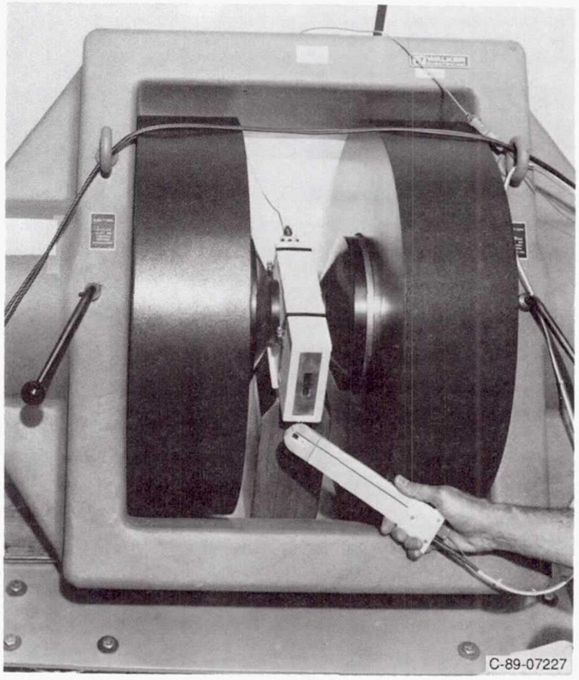

Figure 3.—Magnetics test fixture.

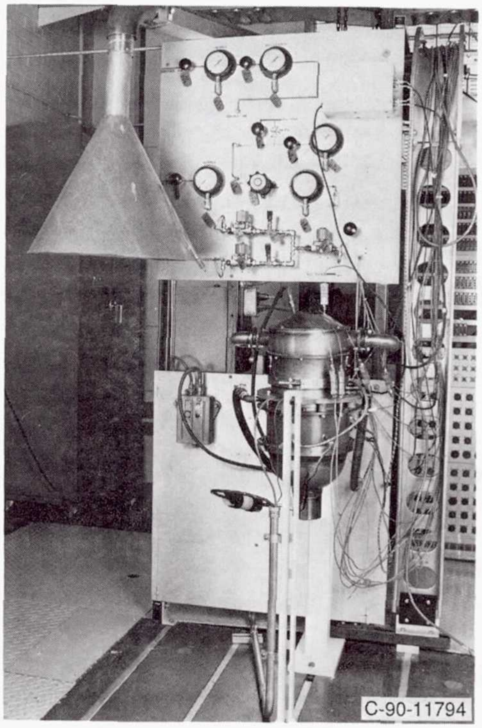

Figure 4.—SPIKE interactions and controls test rig.

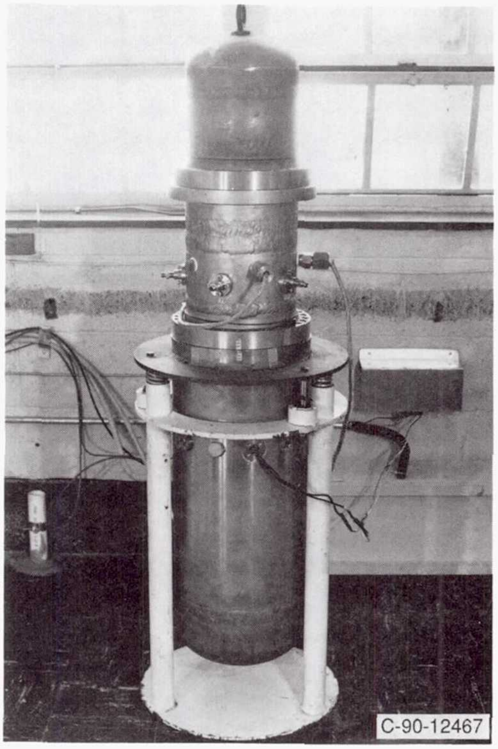

Figure 5.—Regenerator heat transfer test rig.

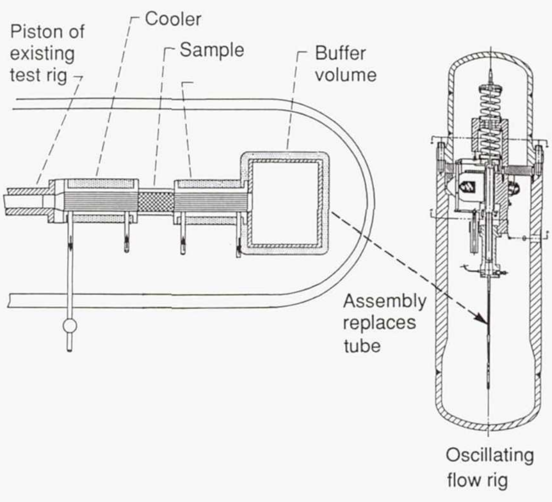

Figure 6.—Regenerator heat transfer tests at Ohio University.

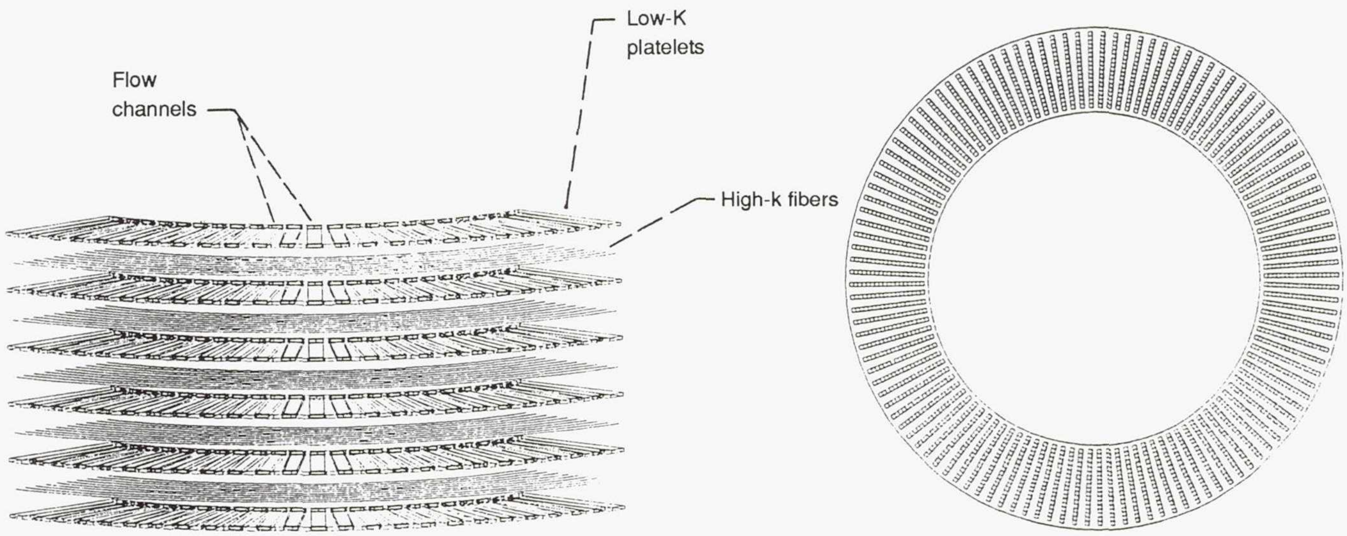

Figure 7.—ESL I anisotropic composite regenerator. Annular regenerator section shows layers of circumferential high-k fibers alternating with low-k platelets having slots for the flow channels. Flow direction is vertical.

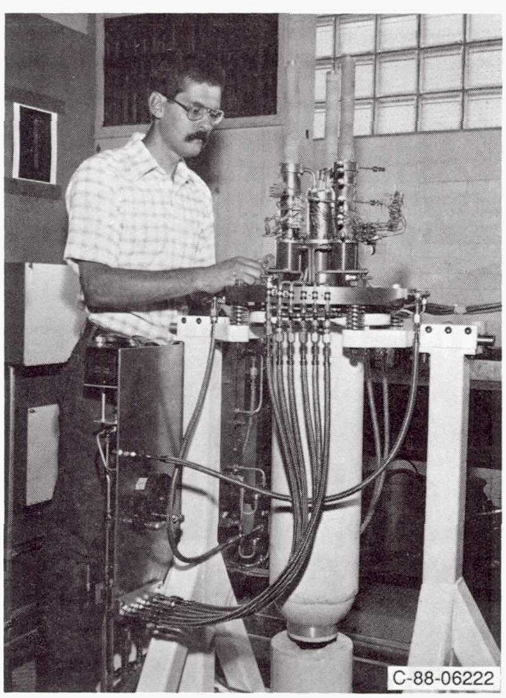

Figure 8.—HP-1000 heat pipe Stirling engine.

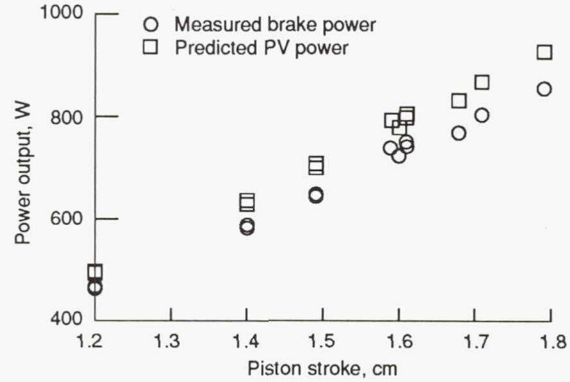

Figure 9.—Comparison of HP-1000 measured brake power to PV power predicted by GLIMPS (600 °C hot-end temperature, 7 MPa pressure).

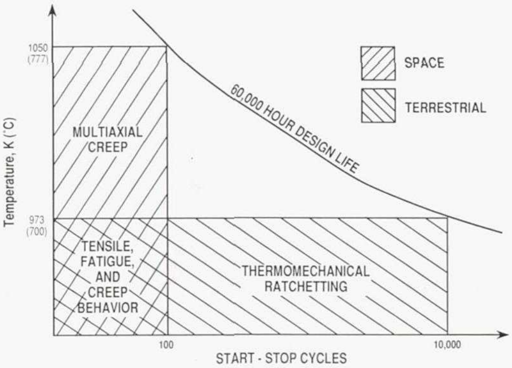

Figure 10.—Design considerations for Stirling engine heater heads.

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