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Summary of the NASA Lewis Component Technology Program for Stirling Power Converters

Lanny G. Thieme and Diane M. Swec
Lewis Research Center
Cleveland, Ohio

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by

Lanny G. Thieme and Diane M. Swec
National Aeronautics and Space Administration
Cleveland, Ohio 44135

ABSTRACT

This paper presents an update on the NASA Lewis Stirling component technology program. The component technology program has been organized as part of the NASA Lewis effort to develop Stirling converter technology for space power applications. The Stirling space power project is part of the High Capacity Power element of the NASA Civil Space Technology Initiative (CSTI). Lewis is also providing technical management of a DOE-funded project to develop Stirling converter systems for distributed dish solar terrestrial power applications. The primary contractors for the space power and solar terrestrial projects develop component technologies directly related to their project goals. This Lewis component technology program, while coordinated with these main projects, is aimed at longer term issues, advanced technologies, and independent assessments. Topics to be discussed include bearings, linear alternators, controls and load interaction, materials/life assessment, and heat exchangers.

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 NASA Lewis Stirling program is described in references 1 and 2. The focus for the Stirling space power effort is the development of a 12.5-kWe/cylinder Stirling converter operating at a hot-end temperature of 1050 K and a temperature ratio of 2.0. Goals include a lifetime of 60,000 hours, an efficiency of 25 percent (heat in to electric power out), and a specific mass of 6 kg/kWe. This work is primarily being done by Mechanical Technology, Inc. (MTI), Latham, New York under contract to NASA Lewis. The converter currently being built under this contract is the 12.5-kWe/cylinder Component Test Power Converter (CTPC). The CTPC is being used to develop the technologies needed to meet the final goals of the contract. This converter will have a limited lifetime at 1050 K, as the hot end will be made from Inconel 718; to meet the life requirement, Udimet 720LI will be used for the final converter of the contract. The cold end of the CTPC has been fabricated and is under test at MTI. A significant milestone was achieved with the successful demonstration of both the internally-pumped hydrostatic gas bearings and the linear alternator operating at the 525 K cold-end design temperature. The hot-end components are now being fabricated, and testing of the complete CTPC converter will follow.

NASA Lewis is also providing technical management of a DOE-funded project to develop Stirling converter systems for distributed dish solar terrestrial power applications. This Advanced Stirling Conversion System (ASCS) project is discussed in reference 3. The design requirements for the ASCS include a 25-kWe output and 33 percent system efficiency (heat in to electric power out). The lifetime goal is 60,000 hours. A converter hot-end temperature of 973 K has been chosen to meet the project requirements and goals. Parallel contracts for the ASCS project have been awarded to Cummins Power Generation, Columbus, Indiana and Stirling Technology Company (STC), Richland, Washington.

The NASA Lewis component technology program is coordinated by the Stirling Technology Branch of the Power Technology Division; it is conducted through in-house and contractor programs utilizing industry, universities, NASA Lewis research and matrix organizations, and other government agencies. The primary contractors for the space power and solar terrestrial projects develop component technologies directly related to their project goals. This Lewis component technology program, while coordinated with these main projects, is aimed at longer term issues, advanced technologies, and independent assessments. It is hoped that, in particular, advancements can be made in lower priority areas of the primary space power contract, these being reduced specific mass and improved understanding of long-life issues.

The objectives of the Lewis component technology program are as follows:

1) To evaluate alternate approaches to the critical converter technologies.
2) To augment the component technology work for the converter designs of the primary contract efforts.
3) To evaluate advanced concepts for future design improvements.
4) To enhance NASA Lewis' expertise and understanding of technology issues.

This paper will focus on those areas that have produced significant results over the previous year. Other efforts will only be mentioned briefly. The references include more detailed papers that have been written by the individual researchers in the various areas of this component technology program.

BEARINGS

Bearings are one of the critical technologies for the power converter, both to achieve successful mechanical operation as well as the long-life potential. The objective is to evaluate alternate bearing approaches. The requirements are to achieve stable, non-contacting operation for 60,000 hours, maximize reliability over the life, and minimize bearing losses.

The current bearing design for the CTPC uses hydrostatic gas bearings. Alternate approaches under investigation in the component technology program include magnetic bearings and flexures. Also, an effort has recently been initiated for hydrodynamic gas bearings; these bearings are currently the selected approach for the Cummins ASCS project and, previously, were demonstrated experimentally for the power piston of the Space Power Research Engine (SPRE) in testing at MTI. A hydrodynamic gas bearings code developed as part of the ASCS project is described in reference 4; both plain cylindrical bearings and a waved bearing concept are analyzed in this reference. A grant with Case Western Reserve University, Cleveland, Ohio has been started to characterize both the cylindrical and wave-contoured bearings in a test rig with cyclic pressure variations across the bearing. This data will be used for validating bearings codes.

Magnetic Bearings

The feasibility of magnetic bearings for free-piston Stirling space power converters was evaluated by the NASA Lewis Structures Division through a contract with MTI. The benefits identified for magnetic bearings (relative to the baseline hydrostatic gas bearings) include no contact during startup and shutdown, converter operation at lower strokes, increased bearing clearance which reduces difficulties both in manufacturing and in designing for differential thermal expansions at the 525 K operating temperature, and less susceptibility to particle contamination. MTI based this feasibility study on the design for the Reference Stirling Space Power Converter (RSSPC), a reference design used to guide the technology development of the primary space power contract.

Magnetic bearings were found to offer a viable alternative for the power piston of the RSSPC. Magnetic bearings for the absolute (sprung-to-ground) displacer of the RSSPC were judged unacceptable for space power applications, as they required an increased pressure vessel diameter. An increased pressure vessel diameter increases the converter specific mass. However, magnetic bearings for both the power piston and displacer were feasible for a relative (sprung-to-piston) displacer version of the RSSPC.

A four-sector, actively-controlled, all-electromagnetic bearing was selected for this study based on its stiffness capabilities, technical maturity, and application experience. A cross-section of the power piston bearing is shown in figure 1. A nonlinear dynamic analysis was performed on the complete bearing system. Stable magnetic bearing configurations are feasible but require careful analysis of all significant parameters. Results of the bearing design and dynamic analysis indicate that dynamic displacements of the bearings during normal operation should not exceed 25 percent of the nominal gas spring seal clearances.

The maximum gain in converter efficiency due to the magnetic bearings was 0.4 percentage points (for the relative-displacer RSSPC with magnetic bearings on both the displacer and power piston). Converter mass increased about 0.5 kg/kWe for this configuration.

Magnetic bearings alleviate the main concerns of the hydrostatic gas bearings - contact on startup and shutdown, and plugging of the bearing orifices. However, they raise other concerns. These include the increased complexity and its effect on long-term reliability, the development of long-life coils capable of operation at the 525 K temperature (an issue shared with the linear alternator), and the increased number of feedthroughs in the pressure vessel. Also, the system mass reductions due to the small increase in converter efficiency will not offset the increased converter mass due to the magnetic bearings, causing power system mass to increase somewhat.

Based on this study, MTI recommended that the hydrostatic gas bearings should remain the system of choice for the space power converter. The magnetic bearings do provide a feasible alternative and should be evaluated further, along with other alternative bearing concepts, if future testing raises long-term concerns with the hydrostatic bearings. Results of this study are discussed in more detail in references 5 and 6.

Flexures

Flexing-metal systems have achieved long lifetimes in low-power, short-stroke Stirling configurations, as described in reference 7. For example, a Thermomechanical Generator using an edge-clamped flat diaphragm ran for over 100,000 hours before being taken out of service. Also, STC has operated an artificial heart assist engine with a flexural bearing at the hot end of the displacer for 60,000 hours, including a continuous run of 36,000 hours. For the higher power applications of interest to NASA, a flexural suspension must achieve long life at the longer strokes typical of Stirling converters with high power density and efficiency; a compact arrangement is also required to minimize mass. A successful flexure offers no contact on startup and shutdown, less complexity, and additional design freedom to achieve the seal requirements with larger clearances, compared to the baseline hydrostatic gas bearing.

Clever Fellows Innovation Consortium, Inc. (CFIC), Troy, New York has begun evaluation of a flexural suspension for the power piston of a Stirling converter. Part of this work was performed under a NASA Phase I SBIR contract. Two flexures were designed, built, and tested for fatigue with a goal of achieving 10 million cycles. One of the configurations, a strap and ring flexure, is shown in figure 2. Also shown is one strap from the second flexure concept, a bent strap configuration.

Each flexure was tested at a stroke of 20 mm, the stroke of the Space Power Demonstrator Engine (SPDE). Strokes up to 40 mm appear feasible for both configurations. The bent strap flexure achieved over 12 million cycles, successfully reaching the demonstration goal. The strap and ring configuration suffered two separate single-strap failures, occurring at 8.5 and 9.8 million cycles. Both were fretting failures and were attributed to the method used to attach the strap to the ring. This type of failure is not considered to be intrinsic to the concept, and design improvements have been identified. Project limitations precluded further testing under this program.

The bent strap design has been selected as the primary concept for further efforts based on its simpler geometry, easier fabrication, and reduced axial stiffness (desirable to readily achieve the longer strokes). Its radial and torsional stiffness are reduced relative to the strap and ring design but should be adequate for use with the unique linear alternator configuration that is being investigated as part of the SBIR program (see Linear Alternators).

STC has explored the use of flexures in a technology assessment task performed as part of the ASCS project. STC evaluated the feasibility of flexures both for implementing non-contact clearance seals and for providing much of the required spring stiffness. The results of this technology assessment are discussed in reference 8.

LINEAR ALTERNATORS

The two primary objectives for linear alternators are to reduce the mass of the alternator and associated structure and to improve the lifetime potential of the alternator operating at high temperatures (525 K). Reducing the alternator mass has the potential for significantly reducing total power system mass. For a nuclear Stirling lunar base, 20 to 30 percent of the system mass is in the power converter, and about 1/3 of this is in the linear alternator. A further objective is to achieve linear alternator efficiencies above 90 percent while reducing the alternator mass. A 1 kg/kWe reduction in converter mass (at constant converter efficiency) yields about the same reduction in system mass as does a gain of 2-1/2 to 3 percentage points in converter efficiency (at constant converter specific mass).

Several linear alternator efforts were described in reference 9 and will be discussed only briefly here. The in-house design of the linear alternator test rig has been completed; however, project limitations have precluded continuing into fabrication. As a possible lower-cost, lower-risk alternative, checkout has begun on an existing mechanical driver that was used as a seals test rig in the automotive Stirling program. This rig is now being converted to a linear alternator test rig and is shown in figure 3, as installed in a NASA Lewis test cell.

Analysis efforts continue at NASA Lewis and under contract with Hollidaylabs, Guysville, Ohio. In-house work is focused on the assembly of a first-order design and evaluation tool. Hollidaylabs is developing advanced analysis procedures for moving magnet linear alternators to improve the accuracy of the magnetic flux calculations and, in particular, to rigorously model the effects of the moving magnet.

Finally, the permanent magnet test facility is being updated to prepare for long-term aging tests at temperatures up to 575 K. Also, short-term tests were completed on $SmCo_5$ to compare to the previously-tested Sm_2Co_{17} magnets. Results of this previous testing of Sm_2Co_{17} magnets to determine short-term temperature effects are reported in references 10 and 11.

STAR[1] Linear Alternator

As part of the NASA Phase I SBIR discussed previously, CFIC has investigated a unique linear alternator concept known as the STAR alternator. The torsional stiffness of the flexural suspension allowed consideration of non-circular geometries and led to the star-configuration. An end view of the alternator is shown in figure 4. The alternator uses oscillating radial magnet arms attached to a small-diameter plunger core; multi-pole lamination stacks fill the gaps between the magnet arms with a coil on each lamination pole. In Phase I, CFIC evaluated the potential advantages of the alternator/flexural suspension for both space and terrestrial applications. CFIC has been selected for a Phase II SBIR to demonstrate the alternator and suspension in hardware. These concepts are described in more detail in reference 12.

Potential benefits of the STAR alternator/flexural suspension that were identified in Phase I include reduced specific mass, improved reliability and

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[1]STAR is a trademark of CFIC.

long lifetime potential, easier fabrication, and reduced cost. The STAR electromagnetic design is expected to reduce the required mass of the magnets, lamination material, and tuning capacitors. Further mass benefits are expected in the surrounding structure due to the reduced alternator size and the elimination of the piston gas bearing. Figure 5 shows a relative comparison of the SPDE and the sketch of the SPDE modified to incorporate the STAR alternator/flexural suspension. Note that the CFIC Phase I effort was a conceptual evaluation only and, thus, the design is not at the same level of detail as the SPDE.

Reliability and lifetime benefits, identified relative to the baseline alternator, include increased plunger rigidity, improved access for cooling, reduced sidepull, and more conventional fabrication for laminations and coils. Converter efficiency improvements are expected due to reduced flux leakage in the alternator, lower gas spring losses (less reciprocating mass), and elimination of the piston gas bearing losses. Finally, a 13 percent system cost savings was estimated for a solar terrestrial application.

CONTROLS AND LOAD INTERACTION

A test facility has been developed at NASA Lewis to investigate the behavior of free-piston Stirling engine/linear alternator (FPSE/LA) power systems with respect to the electrical load interface. The objectives are: (1) evaluate control strategies; (2) characterize the interaction of the FPSE/LA converter with various electrical loads; and (3) evaluate systems with multiple converters. Analytical models will be developed for both single-converter and multiple-converter systems. Dynamic analysis for a single FPSE/LA-load system is described in reference 13.

A key component of the test facility is the 1-kWe SPIKE free-piston Stirling engine with a linear alternator, shown in figure 6. The SPIKE was originally built by Sunpower, Inc., Athens, Ohio; NASA has obtained several of these engines, built under previous government programs. An important milestone was accomplished when self-sustaining operation of the SPIKE was achieved. The second key component of this facility is the engine load control. The original controller has been replaced with an engine load control system developed in-house. This was necessary due to operating difficulties with the original controller and the lack of controller flexibility for the tests planned. Installation of this computer-controlled, general-purpose load control system has been completed. It will allow for operation of the SPIKE at various voltage and corresponding stroke levels, rather than at the constant voltage of the original controller. The test facility and initial test results are described in reference 14.

Tests are planned which will characterize the steady-state and transient response of the converter to various electrical loads such as DC, resistive AC, reactive AC, and motors. These single-converter tests will support the development of engine/alternator system models, which will be used to simulate space power systems containing both multiple power converters and loads. Long range plans include the operation of a multiple-converter system to evaluate module interaction, load sharing, and system stability issues.

MATERIALS/LIFE ASSESSMENT

The objectives for this work are to: 1) augment the materials efforts for the primary converter projects; (2) evaluate long-life material issues; and (3) assess Stirling converter lifetimes.

Joining High-Strength Superalloys

High-strength superalloys such as Udimet 720 cannot generally be joined by conventional fusion welding techniques due to cracking problems. Udimet 720LI has been selected for the hot-end material of the long-life space power converter; Udimet 720 is also a candidate material for the STC solar terrestrial design. Under the primary Stirling space power contract, MTI is developing specialized electron-beam welding procedures for making the joints to the Udimet 720LI heater head of the long-life converter. As an alternative joining method, Allied-Signal Aerospace Company, Garrett Fluid Systems Division, Tempe, Arizona has defined a transient liquid phase diffusion bonding (TLPDB) process for these joints. The TLPDB process can achieve a high-strength bond joint with a hermetic seal and minimal distortion. The joints under consideration include both joints between Udimet 720LI and Inconel 718 and also Udimet 720LI with itself. The locations of the bond joints to the Udimet 720LI are shown in figure 7. The TLPDB process is described in references 15 and 16; the results of this study are included in more detail in reference 16.

Allied-Signal analyzed the heater head assembly sequence and determined that all the joints could be made to the Udimet 720LI material with only two TLPDB cycles. The first cycle begins the bond for the regenerator outer wall; the second cycle then completes all bonding. A bonding aid similar in composition to Udimet 720LI was selected, with boron as the temperature depressant. Various coating processes were considered for applying the bonding aid. As this was a theoretical evaluation only, tests of bonded joints are required to determine the final bonding parameters and to validate the procedures. Important parameters identified include load, soak time and temperature, heating rate, surface preparation, and bond alloy concentration, thickness, and uniformity. Finally, the effect of TLPDB on the grain size of the base metal was evaluated. This is important for the strength of the joints as well as for the thin condenser walls of the starfish heater head. A certain number of grains, as a minimum, are needed across the condenser wall thickness to meet required mechanical properties. A mockup of the starfish is shown in figure 8.

Allied-Signal also completed a general evaluation of liquid metal compatibility issues for the heat transport systems of the Stirling converter. A conclusion was that tests must be conducted under conditions which simulate expected operational systems as closely as possible. Parameters to consider include liquid metal purity, environmental contamination, flow rates, flow channel geometry, temperature and temperature gradients, and desired lifetimes.

To prepare for the materials technology tasks, a technology review was first performed by Allied-Signal. Based on this review, an alternative fabrication procedure was proposed to ease the difficulties of forming the helium flow passages in the current monolithic starfish heater head. In the alternate concept, each starfish fin would be made in two pieces. The passages could be readily formed in these fin halves, and then the halves joined by the TLPDB process. TLPDB would also be used to join the 50 fins to a top plate and a base to form the starfish. The tradeoff for the easier fabrication of the gas passages is an increase in the number of joints for the heater head.

The NASA Lewis Materials Division has initiated joining studies on Udimet 720LI in support of the space power and solar terrestrial projects. Methods under consideration include electron beam welding, gas tungsten arc welding, and transient liquid phase diffusion bonding.

Liquid Metal Effects on Converter Lifetime

Several efforts are underway to evaluate the effects of liquid metals on long-life material issues. The NASA Lewis Materials Division is conducting an effort with the Energy Technology Engineering Center (ETEC), Canoga Park, California to characterize creep and corrosion in nickel-based superalloys operating in a heat pipe environment. This work was summarized in reference 9. The first set of heat pipes have been fabricated by NASA Lewis and sent to ETEC. The screen wicking of these pipes was installed using a special NASA Lewis-designed mandrel assembly. ETEC will be running the tests and is currently assembling the test rig. ETEC will also fill the heat pipes with sodium using procedures that were developed as part of the CTPC heat pipe design and fabrication.

The use of a sodium heat pipe to input heat to a nickel-based superalloy (such as Udimet 720LI or Inconel 718) heater head raises the concern of nickel transport by the liquid sodium. While pumped loop experiments have shown this effect, it has not been demonstrated conclusively for heat pipes. A preliminary analysis, completed at NASA Lewis and presented in reference 17, has suggested that nickel will be leached from the condenser end by the pure, unsaturated liquid and deposited in the evaporator end. Two problems can be caused: (1) the thin walls of the starfish may be eroded away and (2) the evaporator wick can be blocked and cease proper function. This nickel transport would occur even in low-oxygen environments. A related discussion of corrosion in liquid metal systems is presented in reference 18.

To evaluate the effect of nickel transport on the converter lifetime, experimental inputs are needed. Thermacore, Inc., Lancaster, Pennsylvania has begun a Phase I SBIR program that will investigate insoluble coatings to prevent corrosion on heat pipe condenser surfaces. Corrosion rates on both coated and uncoated tubes will be evaluated as part of this effort. Further rate information may be obtained from the creep and corrosion tests at ETEC and from the ASCS project which is completing liquid metal compatibility tests at both Thermacore and STC. The testing at STC and early results are described in reference 19.

Life Assessment of Stirling Heater Heads

The NASA Lewis Structures Division is conducting a structural life assessment of the Udimet 720LI starfish heater head of the Stirling space power converter. A high temperature data base will be generated for Udimet 720LI. This data will be used to characterize a viscoplastic constitutive model for predicting the time-dependent behavior of the material. This model will then be incorporated into a finite element code, and a time-dependent finite element analysis (FEA) completed to determine the stress and deformation states of the heater head. Finally, long-term durability techniques will be used to assess the starfish life.

The pattern for the heater working-fluid passages in the MTI design has evolved from a "racetrack" hole shape to a staggered circular hole pattern in the fins. This change was made to ease the difficulty of fabricating the passages. Thermal and elastic stress FEA were completed by NASA Lewis on both the racetrack and staggered hole designs. Since the strength of the Udimet 720LI is very sensitive to the temperature level, it is important to accurately assess the maximum fin temperature. The temperature at the primary structural component of the starfish will be at approximately the same temperature as the sodium heat pipe vapor. Currently, this is expected to be about 1060 K.

For the long-term durability assessment, the creep and/or stress relaxation properties of Udimet 720LI need to be understood. To prepare for materials testing, two computer-controlled, servohydraulic test systems have been added to the Materials and Structures Divisions' test facilities. Installation has been completed, and test samples are now being fabricated. MTI has been performing an evaluation to determine the optimal form of the Udimet 720LI for the heater head; currently, the long-life starfish is expected to be made from a combination of cast wrought and powder metal. Both material forms will be tested as part of this program, with MTI and NASA Lewis each producing part of the needed test results. A viscoplastic constitutive model has been selected, and methods of integrating this into an in-house finite element code are now being considered.

The Structures Division is also performing a related effort for the STC and Cummins heater heads of the ASCS project. To date, preliminary thermal and elastic stress analyses have been completed for each of these heater heads. For a long-life assessment for the ASCS project, thermomechanical effects must be taken into account, as the large number of start-stop cycles are a basis for creep ratchetting concerns. The analyses for both space power and solar terrestrial designs are described in reference 20.

HEAT EXCHANGERS

Regenerator Heat Transfer Testing

An oscillating flow test rig, built by Sunpower, Inc. for NASA Lewis under a Phase II SBIR and described in references 9, 21, and 22, has been installed at Ohio University, Athens, Ohio. Reference 22 includes previous test results from pressure drop testing in oscillating flow in tubes and regenerators; these tests were performed as part of the Sunpower Phase II SBIR. The test rig was then loaned by NASA Lewis to Ohio University for use in their Center for Stirling Technology Research (CSTR). The objective of the program is to obtain an improved understanding of regenerator heat transfer in oscillating flow. The oscillating flow test rig, as installed at Ohio University, is shown in figure 9. A schematic of the test rig modified for regenerator heat transfer testing is shown in figure 10. The test rig is unique in that it allows measurement of the regenerator heat transfer at the actual engine operating conditions of frequency and pressure. 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. In conjunction with the test rig, a unique data reduction process has been developed to separate the heat transfer coefficient and the enhanced thermal conductivity, two parameters necessary for more accurate analysis of Stirling engines.

Ohio University has been awarded a NASA Lewis grant to measure the heat transfer in stacked (unsintered) and sintered screen samples and feltmetal samples under oscillating flow conditions. Figures 11 and 12 show typical heat transfer data that can be obtained with the oscillating flow test rig and data reduction process. Figure 11 is a plot of the overall heat flux ratio versus the peak value of the Peclet number for the stacked and sintered screens and two feltmetal samples of different wire diameter. The overall heat flux ratio (measured axial heat flux through the regenerator / molecular gas conduction) is modeled in the form

$$N_q = a_1 Pe_m^{a_2}$$

Figure 12 shows the Nusselt number determined by neglecting enhanced axial conduction versus the instantaneous Peclet number for the screen and feltmetal samples. The form of the Nusselt number model is

$$Nu = a_1 Pe^{a_2}$$

Along with this effective Nusselt number, Ohio University can separate out the Nusselt number and enhanced axial conductivity. The friction factor is also measured and correlated in a form similar to the heat transfer models. The complete results for the screen and feltmetal samples and an evaluation of the experimental error can be found in reference 23.

Modifications are being made to the test rig and the data reduction process to continue to improve the accuracy of the results. Future plans include the testing of additional screen regenerators to evaluate the effects of wire diameter and porosity, feltmetals which are being considered for use in the CTPC, and foil regenerators.

A regenerator test rig, originally developed by Philips Research Laboratories, Eindhoven, The Netherlands and shown in figure 13, is being installed at NASA Lewis to develop in-house regenerator testing capabilities. The test rig is on loan from Stirling Thermal Motors, Inc. (STM), Ann Arbor, Michigan. The Philips rig will be used to characterize the heat transfer properties of current candidate regenerator materials for the CTPC under oscillating flow conditions. Other regenerator materials may also be tested to identify additional candidate materials which would improve converter power and/or efficiency. Once the installation of the test rig has been completed, the rig performance will be verified by testing a regenerator, supplied by STM, with known characteristics.

Anisotropic Composite Matrix Regenerator

Energy Science Laboratories, Inc. (ESLI), San Diego, California has a NASA Phase II SBIR contract to develop a composite matrix regenerator (CMR) for a Stirling power converter. The anisotropy in CMR properties offers performance advantages that cannot be obtained with conventional homogeneous materials. The CMR combines a high thermal conductivity material, such as graphite fibers oriented transverse to the flow axis, with a high heat capacity, low conductivity matrix material such as a ceramic or carbon. These properties allow for a regenerator with increased passage size resulting in reduced pressure drop, while maintaining high thermal effectiveness and low axial conduction loss. The potential technical payoffs include improved performance, lower stress in the regenerator wall, and lower converter specific mass. The regenerator wall stresses would be lower due to the reduced pressure drop for the same thermal effectiveness allowing for the use of a longer regenerator. Converter mass would also be lower since the pressure vessel diameter could be reduced due to a decrease in frontal area needed in the regenerator. In addition, the reduced regenerator stress would allow current power converter configurations, using an annular regenerator, to be scaled to higher power levels. Overall, more design flexibility would be achieved.

ESLI is currently evaluating the fabrication methods for both anisotropic duct and crossflow structures. Planar duct structures investigated have included both scrolled and tubular carbon and ceramic structures. The crossflow structures include felts and oriented carbon fiber structures. The ESLI program also involves measuring regenerator thermal effectiveness and pressure drop, modeling CMR performance and incorporating the correlations into the GLIMPS computer code for simulation of a CMR in a Stirling engine, testing CMR durability in a low-power Stirling engine, and designing and fabricating a prototype CMR for testing in a Stirling engine at NASA Lewis. Reference 24 describes the ESLI test rig for measuring regenerator thermal effectiveness and pressure drop and presents early test results.

HP-1000 Testing

The HP-1000 Stirling engine being tested at NASA Lewis is described in references 25 and 26. The HP-1000, shown in figure 14, is a Sunpower RE-1000 engine with a heater head consisting of three heat exchanger modules with integral sodium heat pipes. The working fluid flows in slots around the periphery of each heater and cooler, and each module contains an annular regenerator. The objectives of the HP-1000 program are: (1) to demonstrate the operation of a Stirling engine with a heat pipe heater head, and (2) evaluate the modular heat pipe/heat exchanger concept. A variation of these slotted module heat exchangers is being used in the CTPC cooler, since they allow for a significant reduction in the number of critical joints compared to a conventional tube and shell heat exchanger. A sodium heat pipe is also used on the CTPC, although it is of a different design.

Previously, it has been shown, in reference 9, that the heat pipes and heat exchanger modules have delivered the predicted (by the GLIMPS computer code) power output. Comparisons have since been made to previous RE-1000 test data, and both measured power and efficiency were similar for the RE-1000 and HP-1000. Recent testing has been completed with the heat pipes oriented against gravity and in the gravity-assisted mode to determine the effect of any excess liquid sodium in the heat pipe collecting at the heater/regenerator interface. Figure 15 shows the HP-1000 inverted for testing with the heat pipes operating in the gravity-assisted mode. In general, measured condenser wall temperature profiles were less uniform for the heat pipes operating against gravity. A typical temperature profile for one of the three heat pipes is shown in figure 16. The temperature near the heater/regenerator interface is lower with the heat pipe operating against gravity, as would be expected with an excess liquid sodium pool. To some degree, each of the three heat pipes exhibited this effect. On one of the pipes, higher temperatures were measured in the upper end of the condenser when operating against gravity, which may be due to a partial dryout of the wick. Following these tests, measurements were made to document component endurance. These test results are described in more detail in reference 27.

CONCLUDING REMARKS

This paper has provided an update on the NASA Lewis component technology program which 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. Accomplishments of the past year include completion of a study on transient liquid phase diffusion bonding, a feasibility evaluation of magnetic bearings, a Phase I SBIR identifying potential benefits for a new concept linear alternator/flexural suspension, and testing of the HP-1000 heat pipe converter with the heat pipes operating against gravity and in the gravity-assisted mode. Other efforts continue to show progress. These include the life assessment of Stirling heater heads, regenerator heat transfer testing in oscillating flow, Phase II SBIR development of composite matrix regenerators, linear alternator analysis, and controls and load interaction testing. New efforts initiated were the conversion of a mechanical driver for possible use as a linear alternator test rig and a Phase I SBIR to investigate insoluble coatings to prevent corrosion on heat pipe condenser surfaces.

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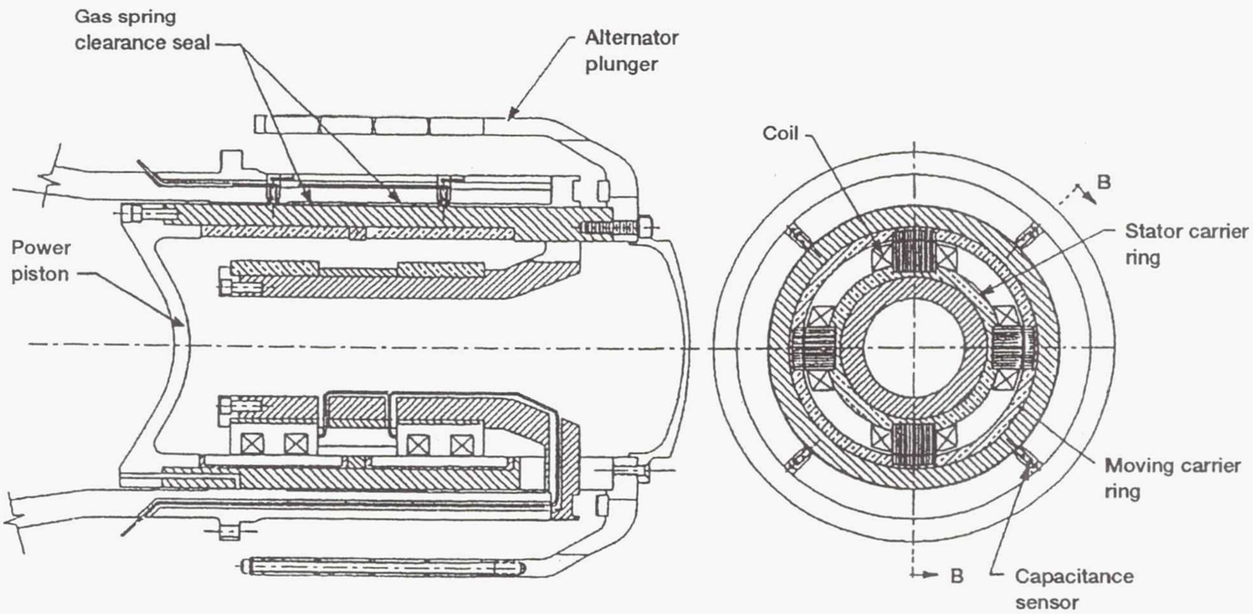

Figure 1.—Magnetic bearing for RSSPC power piston.

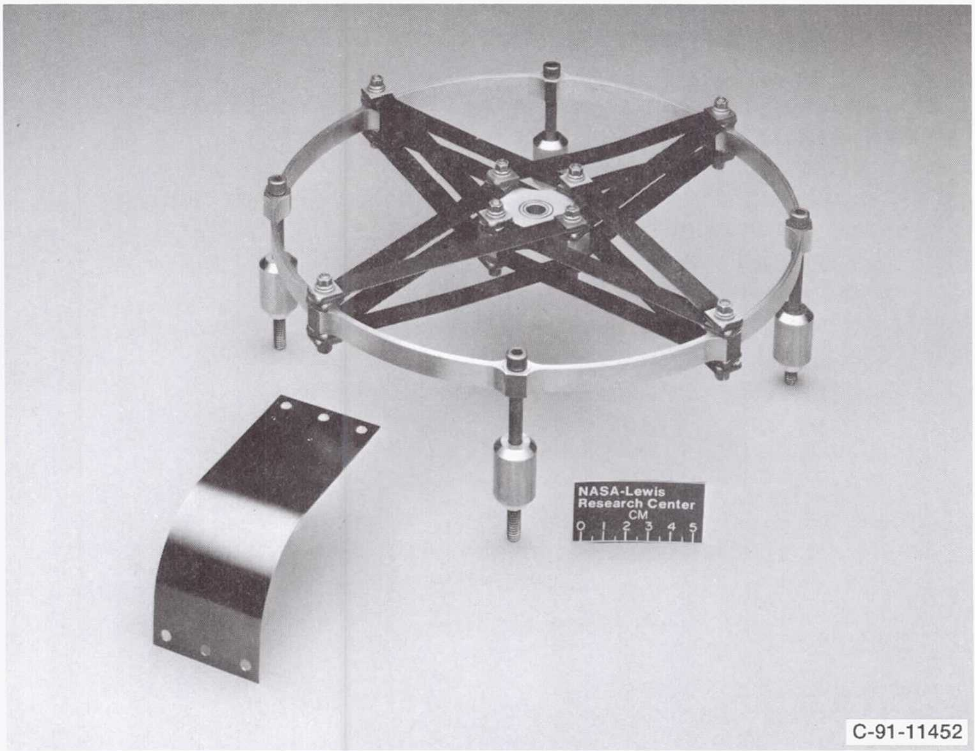

Figure 2.—Strap and ring and bent strap flexures.

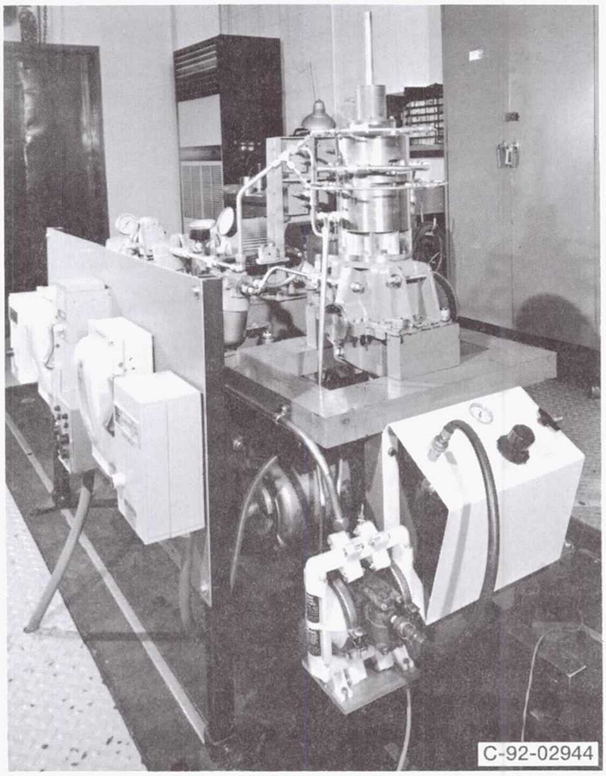

Figure 3.—Mechanical driver for linear alternator test rig.

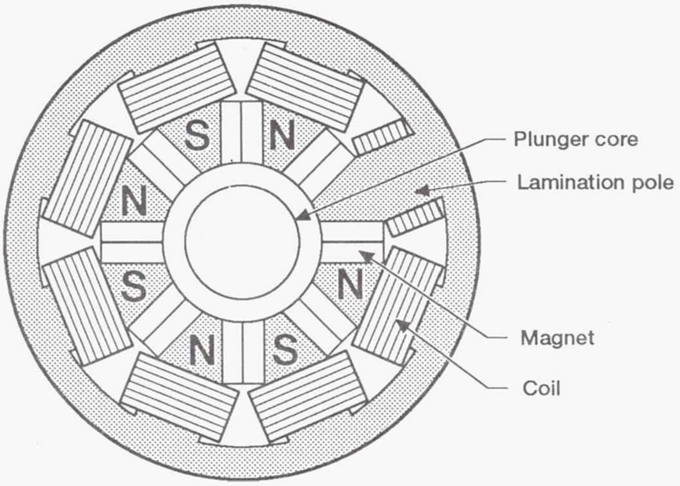

Figure 4.—End view of STAR linear alternator.

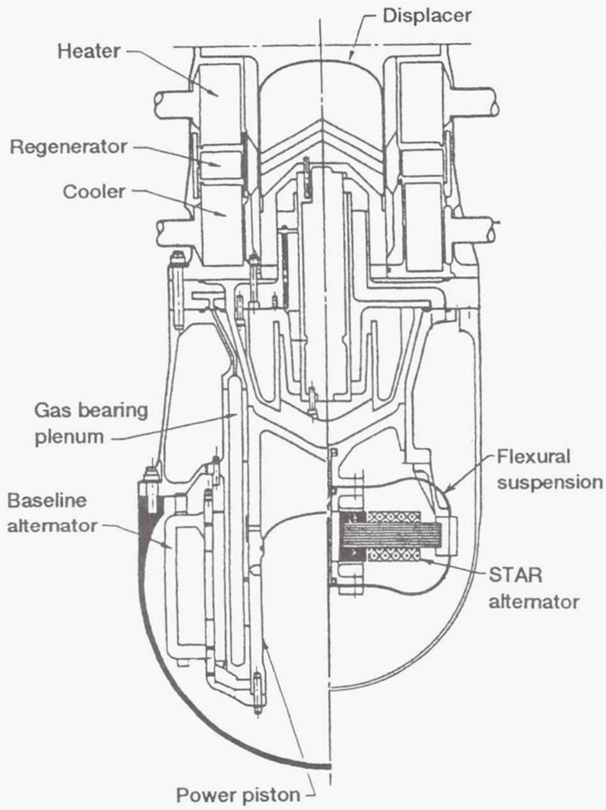

Figure 5.—Comparison of baseline alternator/gas bearing with STAR alternator/flexures in the SPDE.

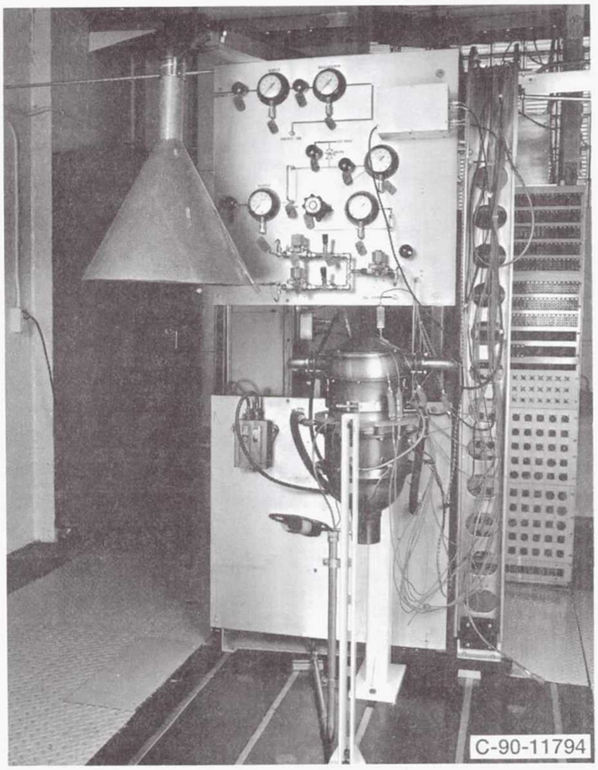

Figure 6.—Controls and load interaction test rig.

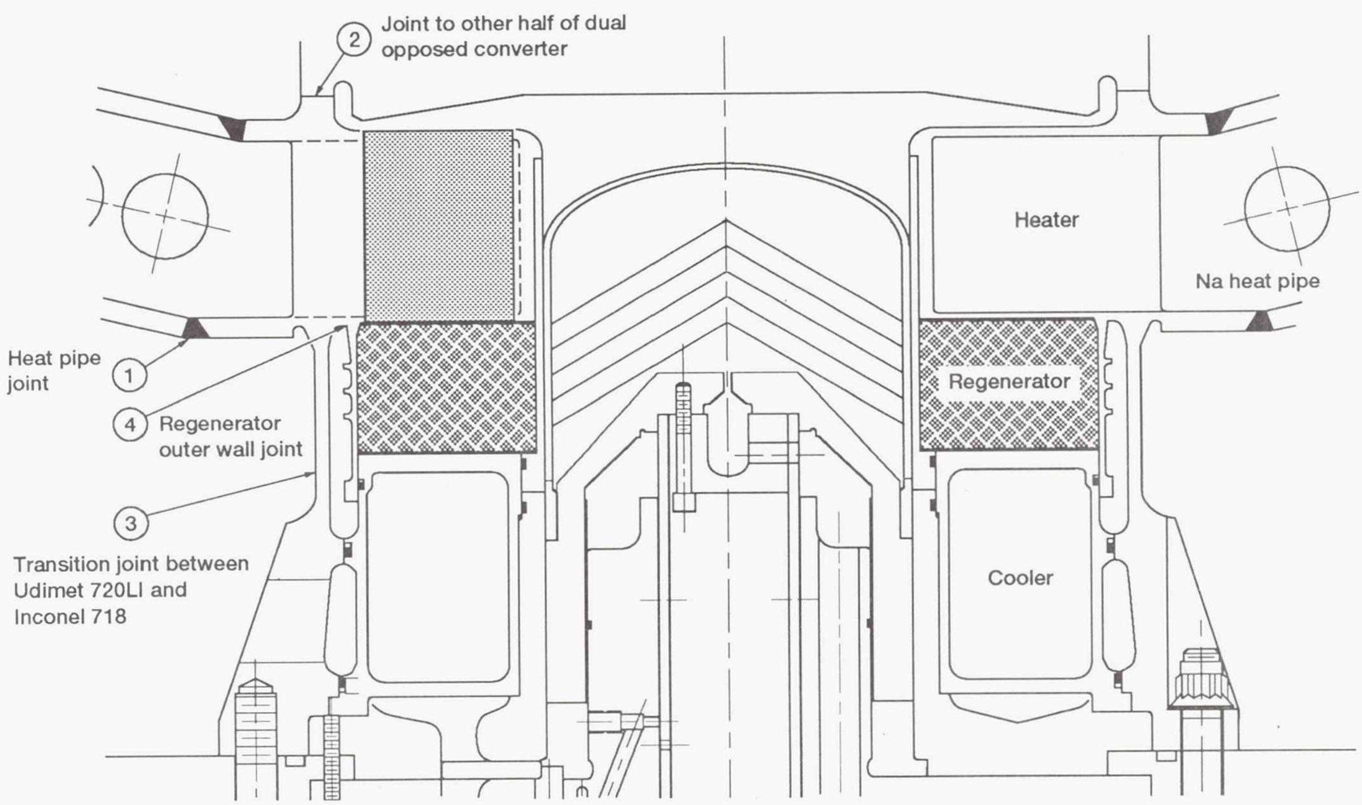

Figure 7.—Udimet 720LI joint locations in starfish heater head.

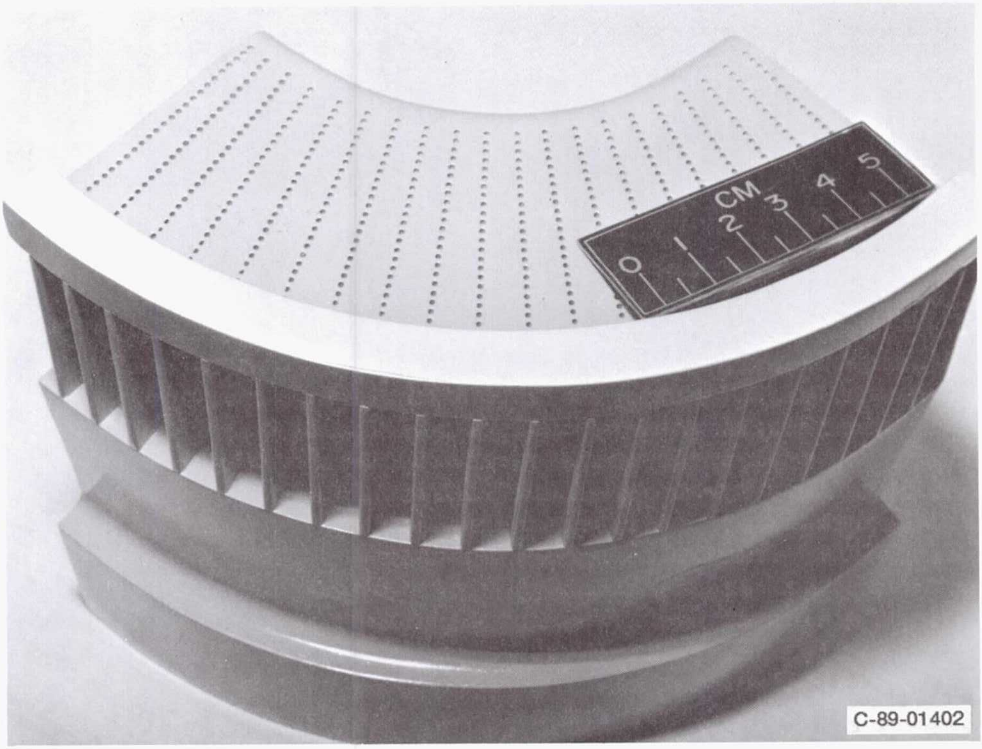

Figure 8.—Starfish heater head.

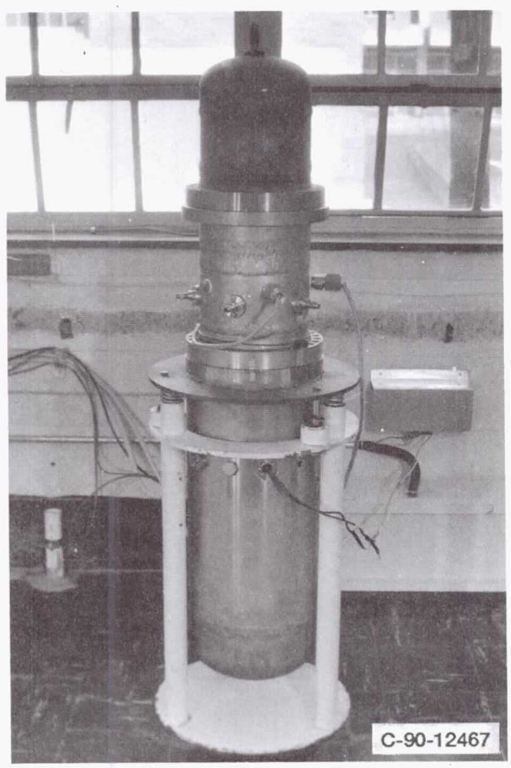

Figure 9.—Regenerator heat transfer test rig at Ohio University.

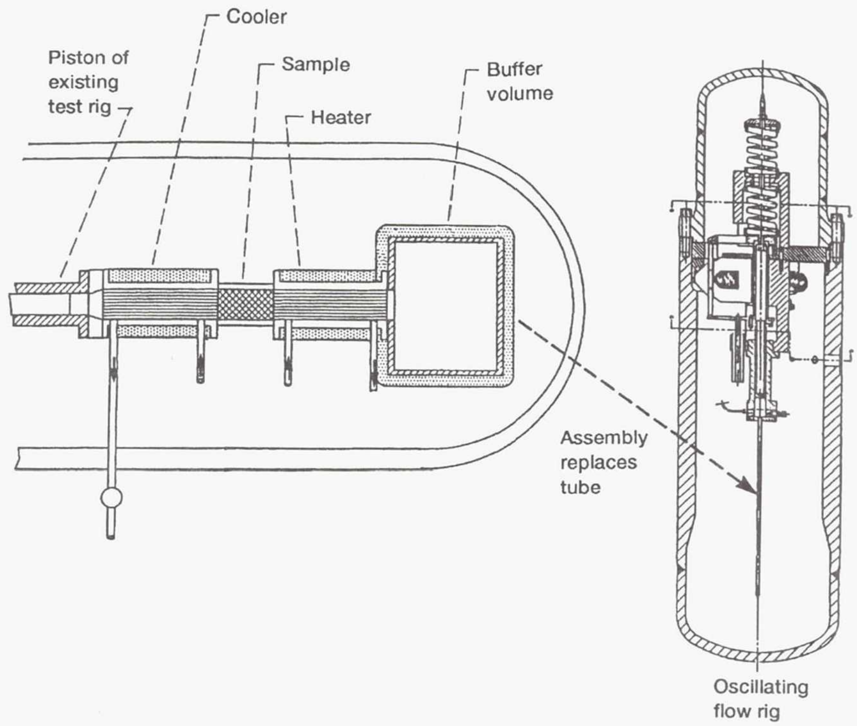

Figure 10.—Modifications to oscillating flow rig for regenerator heat transfer testing.

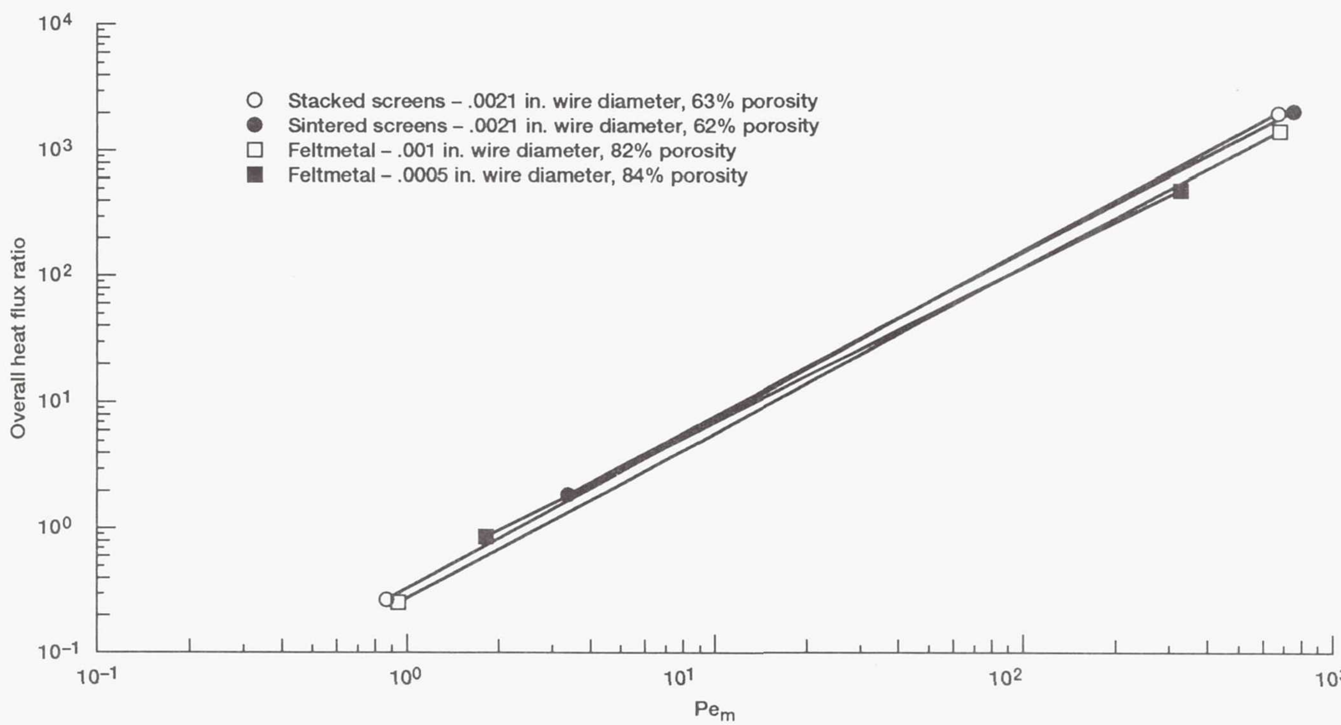

Figure 11.—Overall heat flux ratio (measured axial heat flux through the regenerator/molecular gas conduction) versus peak Peclet number for screen and feltmetal regenerators.

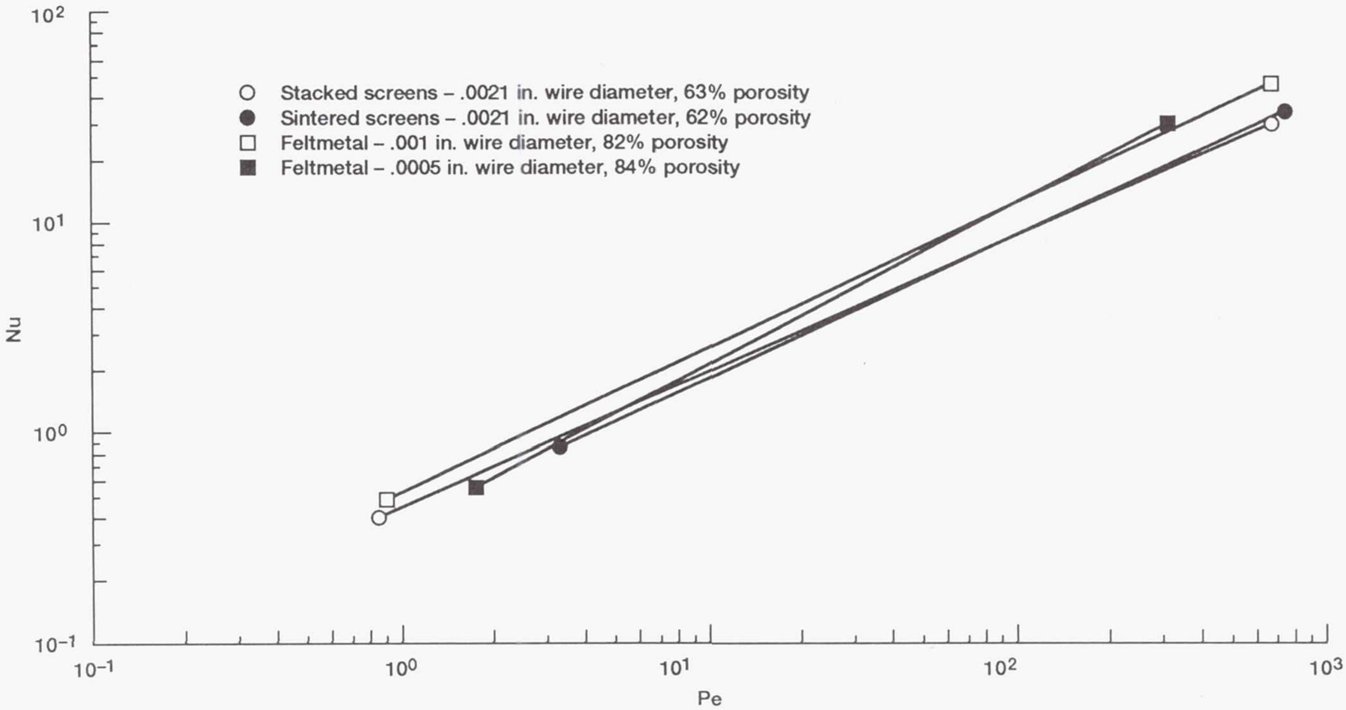

Figure 12.—Nusselt number determined by neglecting enhanced axial conduction versus Peclet number for screen and feltmetal regenerators.

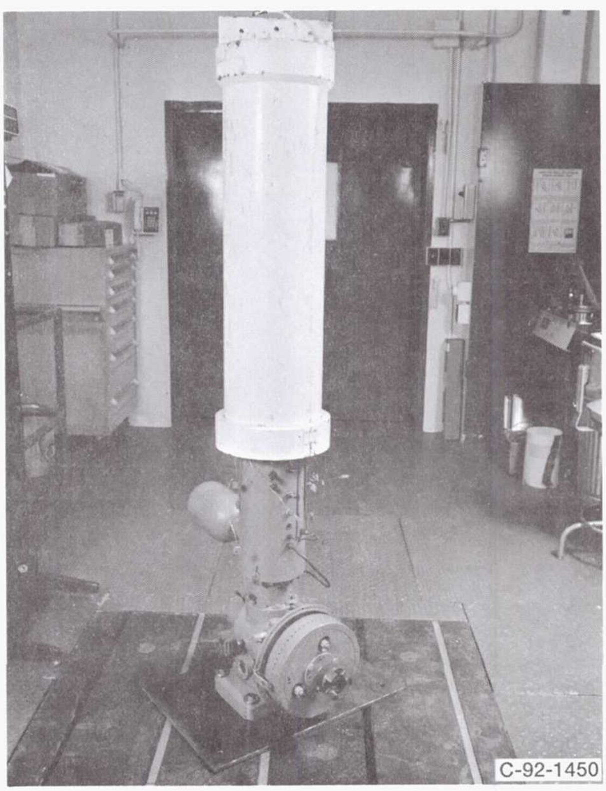

Figure 13.—Philips/STM regenerator test rig.

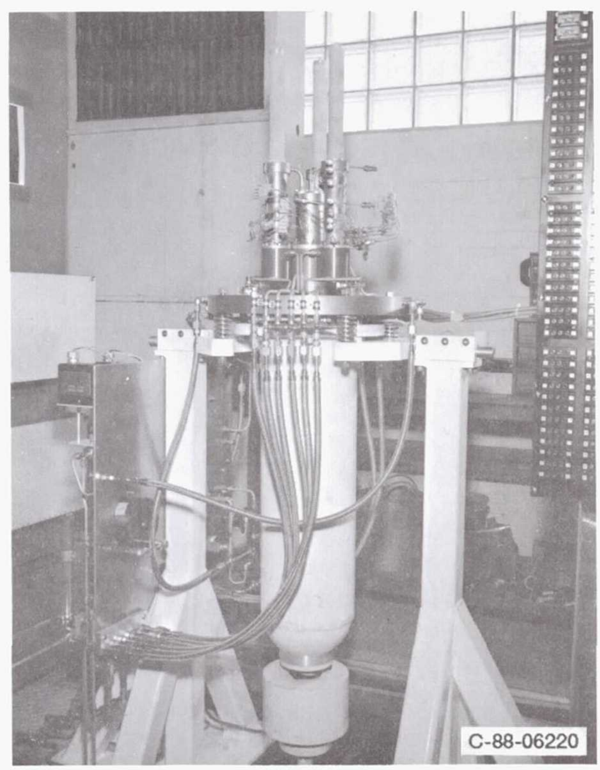

Figure 14.—HP-1000 heat pipe Stirling engine.

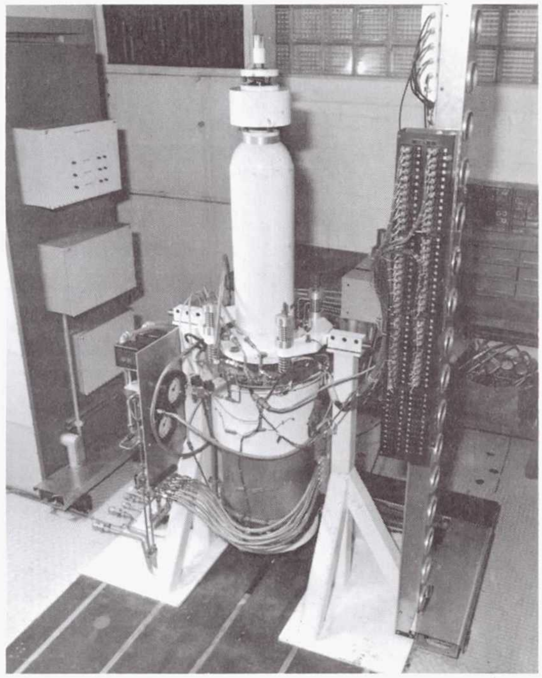

Figure 15.—HP-1000 inverted for testing with heat pipes operating in the gravity-assisted mode.

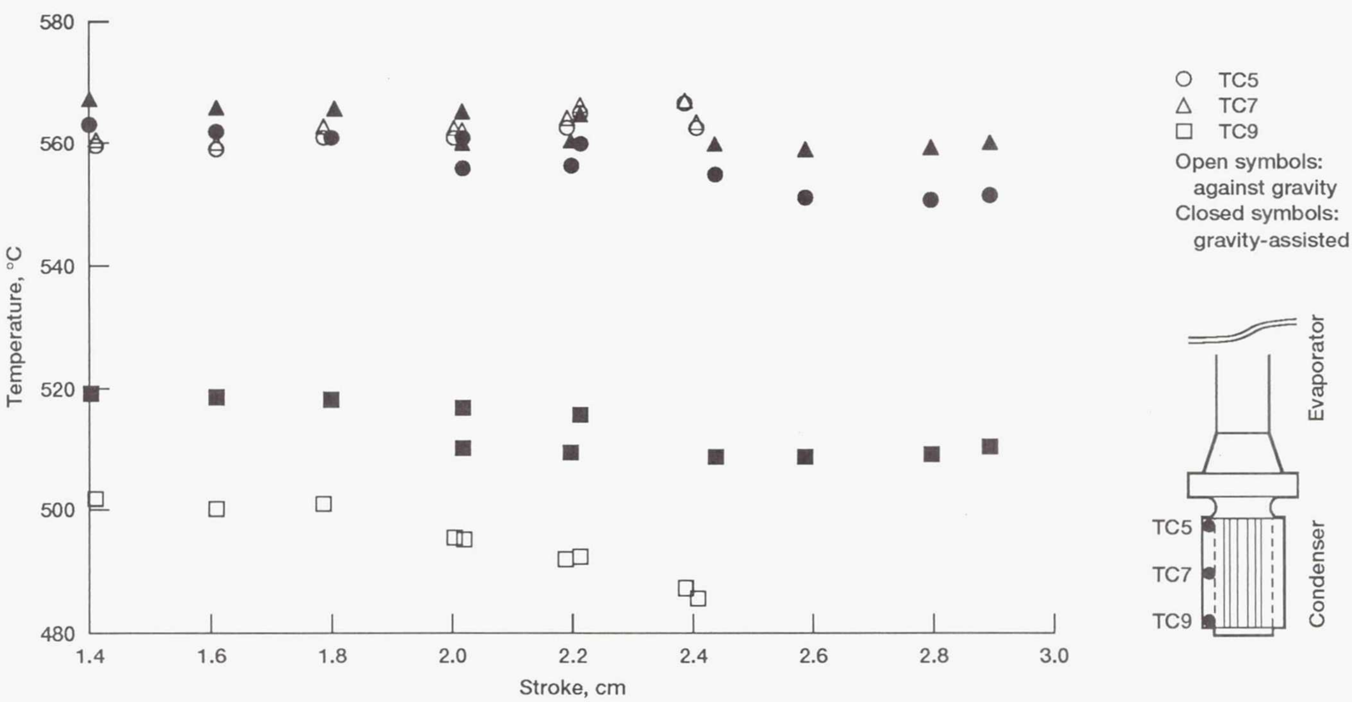

Figure 16.—Condenser temperature profiles for an HP-1000 heat pipe operating against gravity and in gravity-assisted mode.

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13. ABSTRACT *(Maximum 200 words)*

This paper presents an update on the NASA Lewis Stirling component technology program. The component technology program has been organized as part of the NASA Lewis effort to develop Stirling converter technology for space power applications. The Stirling space power project is part of the High Capacity Power element of the NASA Civil Space Technology Initiative (CSTI). Lewis is also providing technical management of a DOE-funded project to develop Stirling converter systems for distributed dish solar terrestrial power applications. The primary contractors for the space power and solar terrestrial projects develop component technologies directly related to their project goals. This Lewis component technology program, while coordinated with these main projects, is aimed at longer term issues, advanced technologies, and independent assessments. Topics to be discussed include bearings, linear alternators, controls and load interaction, materials/life assessment, and heat exchangers.

14. SUBJECT TERMS

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