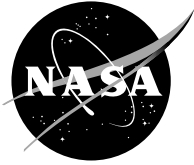


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Supporting Development for the Stirling Radioisotope Generator and Advanced Stirling Technology Development at NASA Glenn

Lanny G. Thieme and Jeffrey G. Schreiber
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February 2005

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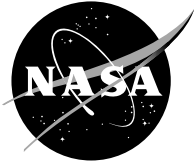
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Abstract

A high-efficiency, 110- W_e (watts electric) Stirling Radioisotope Generator (SRG110) for possible use on future NASA Space Science missions is being developed by the Department of Energy, Lockheed Martin, Stirling Technology Company (STC), and NASA Glenn Research Center (GRC). Potential mission use includes providing spacecraft onboard electric power for deep space missions and power for unmanned Mars rovers. GRC is conducting an in-house supporting technology project to assist in SRG110 development. One-, three-, and six-month heater head structural benchmark tests have been completed in support of a heater head life assessment. Testing is underway to evaluate the key epoxy bond of the permanent magnets to the linear alternator stator lamination stack. GRC has completed over 10,000 hours of extended duration testing of the Stirling convertors for the SRG110, and a three-year test of two Stirling convertors in a thermal vacuum environment will be starting shortly. GRC is also developing advanced technology for Stirling convertors, aimed at substantially improving the specific power and efficiency of the convertor and the overall generator. Sunpower, Inc. has begun the development of a lightweight Stirling convertor, under a NASA Research Announcement (NRA) award, that has the potential to double the system specific power to about 8 W_e/kg . GRC has performed random vibration testing of a lower-power version of this convertor to evaluate robustness for surviving launch vibrations. STC has also completed the initial design of a lightweight convertor. Status of the development of a multidimensional computational fluid dynamics code and high-temperature materials work on advanced superalloys, refractory metal alloys, and ceramics are also discussed.

Introduction

Under the auspices of NASA's Prometheus project, the Department of Energy (DOE), Lockheed Martin (LM) of Valley Forge, Pennsylvania, Stirling Technology Company (STC) of Kennewick, Washington, and NASA Glenn Research Center (GRC) are developing a high-efficiency, nominal 110- W_e (watts electric) Stirling Radioisotope Generator (SRG110) for possible use on future NASA Space Science missions. The SRG110 is being developed for multimission use (e.g., in operating environments with and without atmospheres); potential missions include providing electric power for unmanned Mars rovers and deep space missions. The SRG110 would provide a high-efficiency power source alternative to Radioisotope Thermoelectric Generators (RTGs). The SRG110 system efficiency of greater than 20 percent would reduce the required amount of radioisotope by a factor of four or more compared to RTGs.

LM, under contract to DOE, is the System Integration Contractor for the SRG110. LM is now developing the SRG110 Engineering Unit and will soon be proceeding on the Qualification Unit. The SRG110, described by Cockfield and Chan (2002), is expected to produce at least 112 W_e at beginning-of-mission (BOM), using two opposed Stirling convertors and two General Purpose Heat Source (GPHS) modules. The system efficiency is projected to be 22 to 25 percent with a system mass of less than 34 kg. STC is developing the Stirling convertor for the SRG110. This convertor was originally known as the Technology Demonstration Convertor (TDC). A total of 16 TDCs have been built by STC. The latest four were built with additional quality assurance practices that STC has implemented to prepare for flight convertor fabrication.

Supporting Technology for the SRG110

GRC is conducting a supporting technology project to assist in the flight development of the convertor in preparation for space qualification and mission implementation. This includes independent verification testing of the TDCs, heater head life assessment, materials studies, permanent magnet aging characterization, linear alternator evaluations, launch environment testing, electromagnetic interference and electromagnetic compatibility characterization and reduction, organic materials evaluations, reliability studies, fastener evaluation, and development of an end-to-end system dynamics model and a power system test bed. GRC also provides technical consulting for the TDC development under a Space Act Agreement with DOE.

Heater Head Life Assessment

Heater head life is a critical element for achieving the 14-year life of the convertor. The heater head is a thin-walled pressure vessel fabricated from Inconel 718 (IN718). GRC materials and structures personnel have developed an approach to characterize its long-term durability. This involves both deterministic and probabilistic methods and uses IN718 material testing at GRC, an extensive long-term creep and creep-rupture database (up to 87,000 hours) taken on IN718 by the Oak Ridge National Laboratories (ORNL), and heater head structural benchmark tests to factor in the biaxial stress state and validate the analytical models. Uncertainties and variations in the IN718 material properties, the heater head geometry, and the convertor operating conditions have been considered in the probabilistic analysis. 70 percent of creep rupture life is used as the end-of-life criteria; this is the approximate time to the onset of tertiary creep based on the ORNL IN718 data. The life assessment calculations show a heater head life of 188,000 hours (21.5 years) for a probability of survival (PoS) of 99.9 percent and 116,000 hours (13.25 years) for a POS of 99.99 percent. The life assessment analysis is discussed in Shah, Halford, and Korovaichuk (2004).

Long-term creep testing of the first heat of IN718 material purchased for the convertor heater heads is continuing. The maximum number of hours on a single test specimen is 32,350, as of October 5, 2004, for a stress level of 20 ksi (138 MPa) and a temperature of 650 °C. A second heat of material has now been purchased by LM and STC. Samples of this material have been sent to GRC, and creep testing is underway. Test data for this material will be compared to GRC test data on the first heat of material, and heater head life assessment results will be adjusted as appropriate.

One-, three-, and six-month accelerated structural benchmark tests of heater head pressure vessels have been completed. The thin-walled (0.38 mm thick) pressure vessels for the one- and three-month tests were made by Bitec Sample Machining, Inc. of Dayton, Ohio. The wall thickness and increased pressure levels (relative to the Stirling convertor operating pressure) were used to accelerate the testing and were chosen to reach the onset of tertiary creep in the test time period. The six-month test was completed on a tapered-wall pressure vessel built by STC with the same geometry as used in the SRG110 convertor. Maximum test rig pressure was used for this test, and pre-test calculations showed that the test should approach the onset of tertiary creep. Two remaining twelve-month tests with tapered-wall pressure vessels will be started soon. One will include a brazed heat collector similar to that used in the SRG110 to transfer heat from the GPHS to the Stirling convertor. These tests will be run at the convertor design operating pressure. All tests are run at 650 °C in the gage area at the hot end of the regenerator, which is the primary area of interest for creep.

Figures 1 and 2 show test results for the one- and six-month tests. The creep strain rate is plotted versus test duration. Curves are shown for data from two extensometers measuring the strain in the gage area at positions 90° apart on the circumference. It was found that the shorter one- and three-month (data not shown) tests showed little steady-state secondary creep, while the six-month test did exhibit the more expected trend. The first three-month test gave much higher-than-expected creep rates (based on calculations with mean data) and also showed a large difference between the

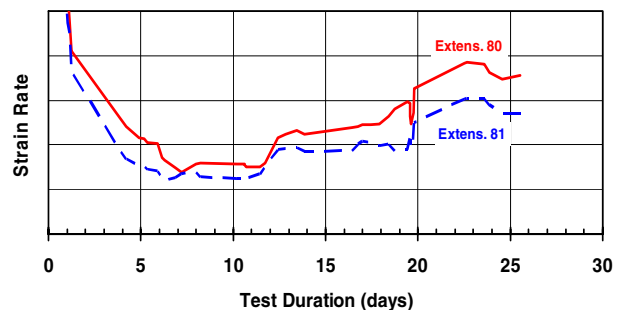


Figure 1.—Creep strain rates measured in one-month heater head structural benchmark test.

two extensometers. This test was repeated and gave reduced creep rates but still a large difference in the extensometer readings. Various tests were completed with the second three-month test specimen that determined the circumferential creep variations were mostly dependent on the test specimen itself and were not strongly related to either instrumentation or heating effects. These test specimens are now being sectioned and examined. The final twelve-month tests will use both extensometers and three-dimensional optical creep strain cameras to measure the very low values of creep that are expected. The cameras will also allow measuring the creep strain over an area as opposed to a point (as with the extensometers).

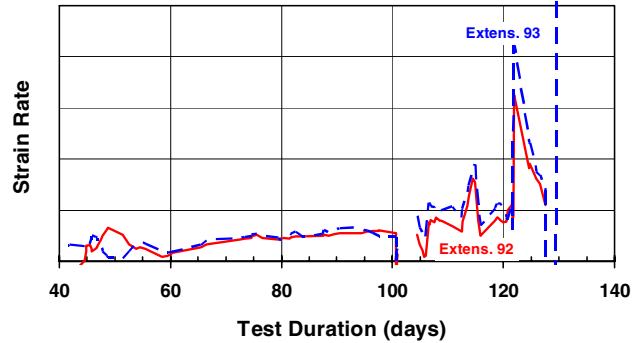


Figure 2.—Creep strain rates measured in six-month heater head structural benchmark test.

Figure 3 shows initial comparisons of the structural benchmark test data to the uniaxial creep data. Stress is plotted versus the initial secondary creep rate. The ORNL curve is the general curve for a large variety of heats tested by ORNL; these tests were done on thick test specimens. The curve labeled “GRC material data” was determined by adjusting the general ORNL curve using the data from the GRC uniaxial creep tests that were done on thin specimens (appropriate for the heater head wall thickness). Also shown are curves approximately representing 99.9 and 99.99 percent PoS. It can be seen that all of the structural benchmark test data fall within the number of standard deviations from the mean curve based on GRC uniaxial test data that correspond to 99.9 and 99.99 percent PoS.

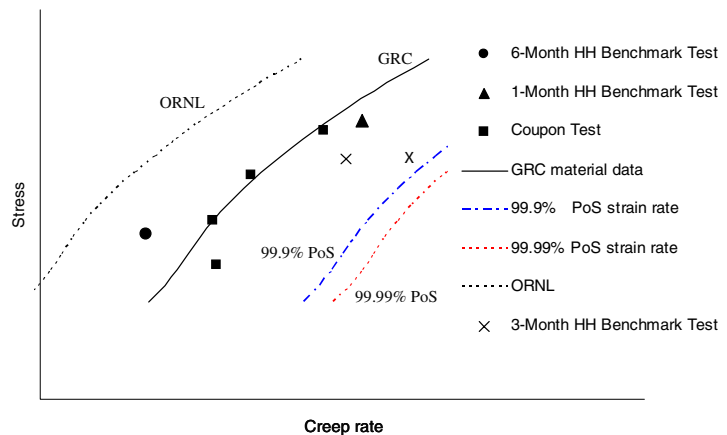


Figure 3.—Comparison of heater head structural benchmark test data with ORNL and GRC uniaxial creep test data and approximate 99.9 and 99.99 percent PoS curves.

Magnet-Stator Bond Evaluation

The GRC Polymers Branch is evaluating the strength and lifetime characteristics of the bond between the permanent magnets and the stator lamination stack in the linear alternator. This bond is made with 3M Scotch-Weld™ 2216 B/A Gray epoxy. GRC recommended a cure cycle for the epoxy based on developing the time-temperature-transformation diagram shown in figure 4 and evaluating lap shear adhesive strength properties at various cure times and temperatures. Working with STC, this cure cycle was then incorporated into the standard processing steps used by STC for fabricating the linear alternator. Lap shear samples cured with this optimized cure cycle showed an increase in adhesive strength of about 40 percent at the expected SRG110 operating temperature, compared to the standard room-temperature cure cycle. A systematic thermal-physical-structural evaluation at various temperatures up to 250 °C showed that the epoxy is stable up to temperatures of 180 °C. Short-term accelerated aging tests of the epoxy (cured with the standard room-temperature cure cycle) were conducted for up to 150 days at 150 and 180 °C. No performance degradation was observed and, as shown in figure 5, the epoxy showed substantial increases in lap shear adhesive strength at 80 and 120 °C after aging at these time and temperature conditions.

While the 2216 epoxy continues to appear a reasonable choice for this application, it is not meant to be a high-temperature adhesive. Two alternate higher-temperature adhesives, Masterbond EP33 and Masterbond Supreme 10HT, were selected by GRC and STC and are being studied as backups to the 2216. Cure kinetics testing has been completed for each Masterbond adhesive.

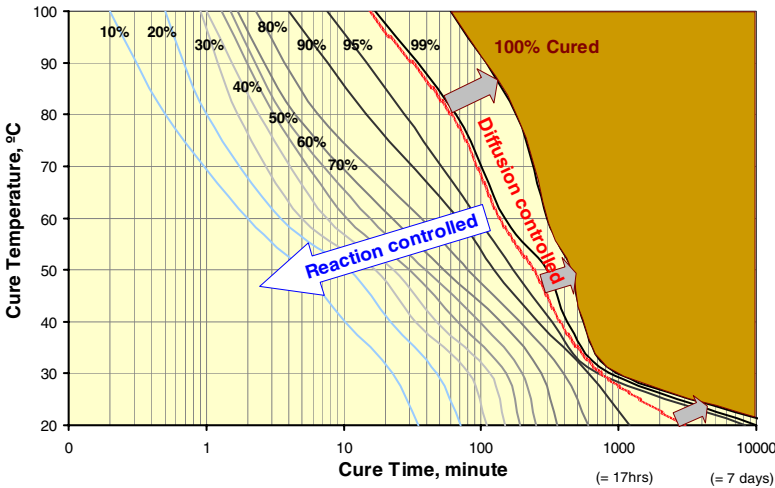


Figure 4.—Time-temperature-transformation diagram showing the cure kinetics of 3M Scotch-Weld™ 2216 B/A Gray Epoxy.

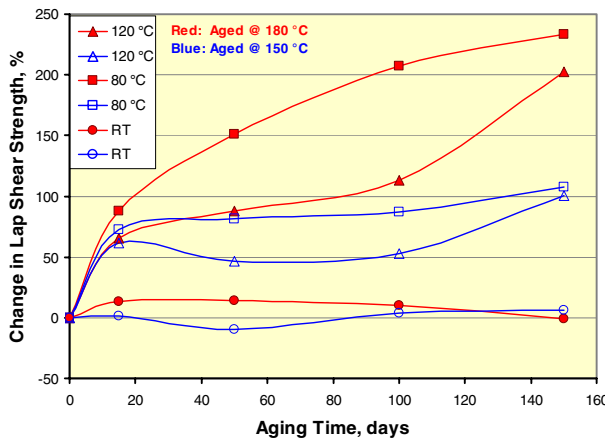


Figure 5.—Percent change in lap shear strength at various temperatures for 3M Scotch-Weld™ 2216 B/A Gray Epoxy with aging time and temperature; RT: room temperature.

Two key series of tests remain: fatigue and lifetime testing. STC is building component-scale test assemblies of the magnet-lamination stack bond that will be used in both series of tests. Cincinnati Testing Laboratories of Cincinnati, Ohio, will be conducting strength and fatigue testing of these component-scale test assemblies. Tests of smaller-scale test assemblies will be done at GRC that will allow testing over a wider range of conditions and more repeat tests at a given condition. GRC is also preparing aging tests of 1/3, 1, and 3 years of component-scale and smaller-scale test assemblies, lap shear test specimens, and epoxy resin sheets for each of the three epoxies

being studied. These aging tests will be run in helium at the convertor design pressure and the maximum expected operating temperature of the bond. Static and dynamic strength tests and property evaluations will be conducted after each aging test.

Other Tasks

An extended operation test of two flight prototype convertors, TDCs nos. 13 and 14, is being conducted in the GRC Stirling Research Laboratory (SRL). 10,115 hours of testing have been completed as of October 3, 2004. TDCs nos. 13 and 14 were recently moved to a new test facility that will include six test stands. A Power System Test Bed will be located in the center of these test stands and will be capable of simulating a variety of spacecraft power systems and

accepting power from any combination of convertors on test. Preparations have nearly been completed for beginning a three-year thermal vacuum test of two convertors, TDCs nos. 5 and 6. Heat will be supplied with an electric resistance heater to simulate the GPHS and will be transferred to the Stirling convertor through a heat collector similar to that used on the SRG110. Heat will be rejected to radiator panels through a cold flange and then to the cold wall of the thermal vacuum facility. A system bakeout of over 900 hours has been completed, and thermal vacuum testing will soon be initiated. Testing in the SRL is described in more detail by Schreiber and Thieme (2004).

GRC has established an extensive reliability effort, led by the Risk Management Office, that is focusing on probabilistic techniques. Tasks include probabilistic reliability analysis of the convertor, including analysis of the individual key components; detailed deterministic analysis of the convertor fasteners; and cataloging long-life Stirling cryocooler and power convertor data for analysis. These reliability efforts are discussed by Schreiber and Thieme (2004).

The development of an end-to-end System Dynamics Model (SDM) is continuing. This model includes the Stirling engine thermodynamics, linear alternator, controller, and case and mounting dynamics. Single or multiple convertors can be simulated in various mechanical and electrical configurations and with a variety of controllers. The model is a non-linear, time-domain model containing sub-cycle dynamics, allowing it to simulate transient and dynamic phenomena. Validation work is underway, and the model capabilities continue to be improved. An interface with the

Sage Stirling code is being added to improve predictions of Stirling cycle thermodynamics. The SDM is being utilized for controller development by both GRC and LM and will also be used by GRC for development of low-vibration techniques as part of the advanced Stirling technology development. The SDM is described by Lewandowski and Regan (2004).

Advanced Stirling Technology Development

GRC is also developing advanced technology for Stirling convertors, with the goal of substantially improving the specific power and efficiency of the convertor and the overall generator. These advances could provide significant performance and mass benefits for Mars rovers and deep space missions and could also allow the use of Stirling radioisotope power systems for radioisotope electric propulsion and Venus surface missions. Performance and mass improvement goals have been established for second- and third-generation Stirling radioisotope power systems. The primary second-generation goal is to double the system specific power to $8 \text{ W}_e/\text{kg}$. Third-generation goals include a system efficiency of 30 to 35 percent and a specific power of $10 \text{ W}_e/\text{kg}$ or greater. Tasks underway to achieve these goals include development of a multidimensional Stirling computational fluid dynamics code, high-temperature materials, advanced controllers, low-vibration techniques, advanced regenerators, and lightweight convertors.

Multidimensional Computational Fluid Dynamics Code

GRC and Cleveland State University (CSU), under grant to GRC, are developing a multidimensional Stirling computational fluid dynamics (CFD) code to significantly improve Stirling loss predictions and assist in identifying convertor areas for further improvements. The University of Minnesota (UMN) and Gedeon Associates of Athens, Ohio are teamed with CSU on the grant effort. The development of the code and the supporting validation effort is also expected to lead to improvements in one-dimensional (1-D) design codes. The current status of this code development and validation is given by Tew et al. (2005).

The commercial code CFD-ACETM has been used by CSU to develop a 2-D model of a Stirling convertor. GRC has modified this for the TDC, and the model will soon be transitioned to three dimensions. One key issue is the amount of processing time needed to run a complete 3-D model of a convertor. GRC has purchased a Microway 32-processor cluster with high-speed communications to significantly increase processing speed. This cluster has now been installed and can be seen in figure 6 on the right side of the photo. On the left is a partial view of an 8-processor Dell cluster that was purchased initially. GRC has recently purchased the commercial code FLUENT, and modeling with this code is also underway. GRC will be comparing parallel versions of FLUENT and CFD-ACETM operating on the computer clusters.



Figure 6.—Parallel computer clusters at GRC.

Several key areas remain to be addressed for the Stirling CFD code developments. Porous media modules included with the commercial codes are now used for simulating the regenerator matrix. These models assume matrix solid and gas temperature equilibrium and need to be replaced by non-equilibrium models that allow these temperatures to be different. Several non-equilibrium models have been identified, and tests at UMN are providing values of empirical coefficients necessary to implement these models. A second key area for further work is accurate modeling of turbulent flow and especially the transition between laminar and turbulent flow. Currently, CFD-ACETM requires assuming one flow regime throughout the model and thus does not model transition. FLUENT has added the capability of Detached Eddy Simulation, which will predict transition in the main flow stream through the use of Large Eddy Simulation (LES); a turbulence model is assumed near the wall to maintain reasonable computation times. It may also be possible to use LES throughout the working space with the use of adaptive gridding. A third area is finding methods to accelerate temperature convergence of solids with large heat capacity that are exchanging heat with gases of small heat capacity. Currently, this problem greatly extends the time required for convergence to a steady-periodic cycle.

New efforts are getting underway to evaluate the use of high-order accuracy numerical techniques to significantly increase the convergence speed for the CFD codes. Initial thoughts have also been given to the development of 2-D and 3-D steady-periodic codes based on techniques similar to those used in 1-D design codes. It is expected that these multidimensional codes could be fast enough to be used for convertor design.

High-Temperature Materials

The maximum hot-end temperature for the SRG110 convertor is 650 °C, with a design lifetime of 14 years. The heater head is fabricated from the nickel-base superalloy IN718. Higher-temperature materials, including advanced superalloys, refractory metal alloys, and ceramics are being evaluated to increase the convertor hot-end temperature (Bowman, Ritzert, and Freedman, 2004). Advanced superalloys could allow operation up to 850 °C, while refractory metal alloys and ceramics could achieve up to about 1200 °C for these required lifetimes. However, the maximum hot-end temperature may need to be restricted to lower temperatures to maintain the radioisotope heat source within its temperature limits. A review is also being performed of the effects of these higher temperatures on other convertor materials, heat losses, and the heat source interface.

A large number of superalloy materials were screened primarily for creep properties, hermetic sealing, and long-term stability. Five nickel-based superalloys with superior creep properties to IN718 were selected in summer 2003 for further study. The materials selected were Udimet 720, IN738LC, IN939, MarM-247, and MA754, with MarM-247 identified as the leading candidate. These materials include wrought, cast, and mechanically-alloyed superalloys and cover a range of potential temperature improvement versus risk tradeoffs. Creep testing on thin specimens of each material is underway with 50,910 total hours of testing complete on 28 specimens, as of October 5, 2004. For the data accumulated to date, MarM-247 has the highest creep strength of the five materials under test. A second heat of MarM-247 has recently been processed to produce finer grains. Specimens from this heat are now being tested for two different thicknesses to allow an optimal material selection to be made.

Refractory metal alloys chosen for further study are a tantalum alloy, ASTAR-811C, and rhenium. Refractory metal alloys typically have a much smaller database than the superalloys, thus making long-term life predictions more uncertain. Also, oxidation effects at the hot operating temperature must be addressed. Both ASTAR-811C and rhenium materials have been received, microstructures have been characterized, and initial creep testing is expected to begin soon. A rhenium specimen will also be tested with an iridium coating to demonstrate the ability to test for thousands of hours in an air environment. To begin addressing any processing issues, a near net shape rhenium heater head demonstration vessel has been successfully fabricated. Specimens will be taken from this heater head vessel for creep testing to compare with the standard creep specimens. A second near net shape heater head vessel will be made to demonstrate the ability to make a thin wall and to machine the wall profile.

Ceramic materials offer a number of significant advantages over superalloys for the Stirling heater head application, including higher-temperature capability, more creep resistance, and a wider range of thermal conductivities. Ceramics may allow tailoring for high radial thermal conductivity and low axial thermal conductivity to minimize convertor heat conduction losses. Also, ceramics do not require testing in an inert environment. The primary issues for developing a ceramic heater head are: 1) helium permeability through the ceramic structure, 2) the ceramic-metal joint, and 3) assembly and testing of the complete heater head structure. Damage tolerance must also be addressed. Helium permeability tests have been completed at room temperature and 0.2-MPa (30-psi) helium pressure on eight candidate materials. Four of these, including silicon nitride and silicon carbide, demonstrated lower permeability than IN718. The next step is to do additional permeability testing at higher temperatures and pressures relevant to the Stirling application. Sample closed-end tubes have been made by different manufacturers and will be included in the permeability testing.

Lightweight Stirling Convertors

Sunpower, Inc. of Athens, Ohio, is developing a lightweight Stirling convertor for radioisotope space power systems under a NASA Research Announcement (NRA) award for Radioisotope Power Conversion Technology (Wood and Carroll, 2005). Based on its projected mass and performance, this lightweight convertor, known as the Advanced Stirling Convertor (ASC), has the potential to double the specific power of a second-generation Stirling radioisotope power system to about 8 W_e/kg. It is sized for two convertors operating in an opposed, balanced configuration and

using the heat from two GPHS modules. Sunpower has teamed with Boeing/Rocketdyne of Canoga Park, California for this development. Major accomplishments of the project's first year include completing the design of the first-generation ASC and designing, fabricating, and beginning tests of a "Frequency Test Bed (FTB)" convertor development unit. The ASC will have a hot-end temperature of 850 °C and is expected to achieve a power output of about 88 W_e and an efficiency approaching 40 percent. The design life is 14 years, and the specific power is estimated at 91 W_e/kg. Operating at frequencies near 105 Hz, the FTB has demonstrated 36 percent efficiency (engine and linear alternator) with heat input to the heater head limited to 220 W and a temperature ratio of 3.0 (650 °C hot-end and 30 °C reject temperatures), the expected temperature ratio for ASC operation.

Sunpower is also developing a nominal 35-W_e convertor under a NASA Phase II SBIR, as described by Wood and Lane (2004). This convertor, known as the EE-35, is sized for two convertors operating in an opposed, balanced configuration and using the heat from one GPHS module. This convertor is designed for operation at 650 °C hot-end and 80 °C reject temperatures. It has achieved over 40 W_e power output with an efficiency of 31 percent. In its final hermetically-sealed configuration, Sunpower estimates that the convertor specific power should exceed 90 W_e/kg.

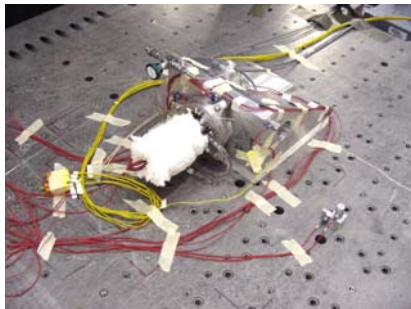


Figure 7.—EE-35 convertor on random vibration test in Structural Dynamics Laboratory.

GRC has purchased four of the Sunpower EE-35 convertors, in addition to two that will be delivered under the SBIR. GRC has completed random vibration testing of two EE-35 convertors to evaluate robustness for surviving launch vibrations (fig. 7). Initially, both units were tested individually up to a generator flight qualification level of 12.3 grms in both axes. Unit 1 was then operated with higher levels of random vibration in the axial direction, with the input reaching 23.9 grms (the limit of the shake table) for one minute; however, the GRC external controller was not able to maintain control throughout the entire test. Initial assessment has shown that Unit 1 was undamaged by the test. Unit 2 was tested to higher levels in the lateral direction, up to 23.9 grms; it was operating properly when an external fill tube broke, and the test was concluded. Previous to this, Unit 2 had operated for the full one-minute duration at 22.9 grms. Initial assessment of Unit 2 was also that it suffered no damage. Power output from both units remained nearly unchanged throughout the tests.

Under GRC funding, STC has evaluated design updates for the SRG110 Stirling convertor to significantly reduce the convertor mass. Improvements were achieved by increasing convertor frequency, reducing linear alternator over-capacity, using a flux concentrating or moving magnet linear alternator design and a flat heater head, and material substitutions. STC estimates that the revised design reduces the convertor mass from about 5.5 kg (with heat collector) to about 1.5 kg, giving a convertor specific power of about 45 W_e/kg for a power output of about 70 W_e. Length and diameter are also substantially reduced. The flat heater head should interface directly with the radioisotope heat source and does not require an additional heat collector. STC also estimates that the thermal to mechanical efficiency should increase from about 55 percent of Carnot to nearly 60 percent of Carnot. This effort is discussed by Qiu, Augenblick, and Peterson (2004).

Other Tasks

Advanced controller development is investigating the elimination of tuning capacitors through the use of active power factor correction (APFC), to reduce controller mass and volume. GRC has completed initial lower-power testing of an APFC controller with a TDC. This testing demonstrated the ability to adjust the power factor and control stroke. Future testing will demonstrate operation at full convertor power output. Rack versions of the APFC controller are being completed for both the TDC and EE-35 convertors. Future work will explore techniques that use the controller to alter the dynamics of one convertor relative to the other to achieve very low levels of vibratory emissions, as may be needed for some applications. The advanced controller development is described by Gerber et al. (2004).

CSU is conducting a research effort for a microfabricated regenerator under a NRA award for Radioisotope Power Conversion Technology. CSU is teamed with UMN, Gedeon Associates, STC, and Sunpower. Microfabricated regenerators could potentially improve Stirling convertor performance, increase regenerator durability, and improve fabrication consistency. In the first year of the effort, several regenerator designs, manufacturing processes, and

manufacturers were evaluated. International Mezzo Technologies of Baton Rouge, Louisiana, was chosen to be the fabricator of an involute approximation of a parallel-plate regenerator. The manufacturing process is a combination of LIGA (lithography, electroplating, and molding) and EDM (electric discharge machining). A large-scale mockup of the design will be tested at UMN, and a regenerator matrix with actual size features will be tested in an oscillating-flow rig at Sunpower. As a final demonstration, a microfabricated regenerator matrix will be tested, as possible, in an actual Stirling convertor. This effort is discussed by Tew et al. (2005).

Conclusions

Key GRC efforts continue for the SRG110 development. Initial comparisons with the heater head structural benchmark test data support the life assessment analysis, as the test data fall within the number of standard deviations from the mean curve for the GRC uniaxial test data that correspond to probabilities of survival of 99.9 and 99.99 percent. Test data taken for the bond of the magnet to the stator lamination stack show that 3M Scotch-Weld™ 2216 B/A Gray epoxy continues to be a reasonable choice for this bond. Stirling advanced technology efforts are also well underway. Advanced Stirling systems could provide significant performance and mass benefits for Mars rovers and deep space missions and could also allow the use of Stirling radioisotope power systems for radioisotope electric propulsion and Venus surface missions. For the creep data accumulated to date, MarM-247 has the highest creep strength of five advanced superalloy materials under test, as options for a higher-temperature heater head. Sunpower lightweight Stirling convertors have shown excellent performance in early testing and have the potential to double the system specific power to about 8 W_e/kg .

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13. ABSTRACT (<i>Maximum 200 words</i>) A high-efficiency, 110-W _e (watts electric) Stirling Radioisotope Generator (SRG110) for possible use on future NASA Space Science missions is being developed by the Department of Energy, Lockheed Martin, Stirling Technology Company (STC), and NASA Glenn Research Center (GRC). Potential mission use includes providing spacecraft onboard electric power for deep space missions and power for unmanned Mars rovers. GRC is conducting an in-house supporting technology project to assist in SRG110 development. One-, three-, and six-month heater head structural benchmark tests have been completed in support of a heater head life assessment. Testing is underway to evaluate the key epoxy bond of the permanent magnets to the linear alternator stator lamination stack. GRC has completed over 10,000 hours of extended duration testing of the Stirling convertors for the SRG110, and a three-year test of two Stirling convertors in a thermal vacuum environment will be starting shortly. GRC is also developing advanced technology for Stirling convertors, aimed at substantially improving the specific power and efficiency of the convertor and the overall generator. Sunpower, Inc. has begun the development of a lightweight Stirling convertor, under a NASA Research Announcement (NRA) award, that has the potential to double the system specific power to about 8 W _e /kg. GRC has performed random vibration testing of a lower-power version of this convertor to evaluate robustness for surviving launch vibrations. STC has also completed the initial design of a lightweight convertor. Status of the development of a multi-dimensional computational fluid dynamics code and high-temperature materials work on advanced superalloys, refractory metal alloys, and ceramics are also discussed.				
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