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Overview of NASA GRC Stirling Technology Development

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May 2004

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Overview of NASA GRC Stirling Technology Development

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ABSTRACT

The Stirling Radioisotope Generator (SRG) is currently being developed by Lockheed Martin Astronautics (LMA) under contract to the Department of Energy (DOE). The generator will be a high efficiency electric power source for NASA Space Science missions with the capability to operate in the vacuum of deep space or in an atmosphere such as on the surface of Mars. High system efficiency is obtained through the use of free-piston Stirling power conversion technology. Power output of the generator will be greater than 100 watts at the beginning of life with the decline in power being largely due to the decay of the plutonium heat source. In support of the DOE SRG project, the NASA Glenn Research Center (GRC) has established a near-term technology effort to provide some of the critical data to ensure a successful transition to flight for what will be the first dynamic power system used in space. Initially, a limited number of technical areas were selected for the GRC effort, however this is now being expanded to more thoroughly cover a range of technical issues. The tasks include in-house testing of Stirling convertors and controllers, materials evaluation and heater head life assessment, structural dynamics, electromagnetic interference, organics evaluation, and reliability analysis. Most of these high-level tasks have several subtasks within. There is also an advanced technology effort that is complementary to the near-term technology effort.

Many of the tests make use of the 55-We Technology Demonstration Convertor (TDC). There have been multiple controller tests to support the LMA flight controller design effort. Preparation is continuing for a thermal/vacuum system demonstration. A pair of flight prototype TDC's have recently been placed on an extended test with unattended, continuous operation. Heater head life assessment efforts continue, with the material data being refined and the analysis moving toward the system perspective. Long-term magnet aging tests are continuing to characterize any possible aging in the strength or demagnetization resistance of the permanent magnets used in the linear alternator. In a parallel effort, higher performance magnets are also being evaluated. A reliability effort is being initiated that will help to guide the development activities with an increased focus on the necessary components and subsystems. Some other disciplines that are active in the GRC technology effort include structural dynamics, linear alternator analysis, EMI/EMC, controls, and mechanical design evaluation. This paper will provide an overview of some of the GRC technical efforts, including the current status, and a description of future efforts.

INTRODUCTION

An assessment of Stirling power conversion technology was performed in 1999 by a joint government/industry team.[1] The purpose of the assessment was to determine the readiness of free-piston Stirling power conversion technology for transition to flight in a high efficiency radioisotope generator for NASA Space Science missions. The assessment used the 55We Technology Demonstration Convertor (TDC) as the basis for the evaluation and concluded that the technology was ready for transition to flight. The TDC was developed by the Stirling Technology Company (STC) of Kennewick, WA under contract with the Department of Energy (DOE) with technical support from the NASA Glenn Research Center (GRC). DOE subsequently initiated an effort to design the generator into which the Stirling convertors are integrated. Following a competitive procurement, Lockheed Martin Astronautics (LMA) of Valley Forge, PA was awarded a contract in May, 2002 to develop the Stirling Radioisotope Generator (SRG). The conceptual design of the SRG has been completed and is shown in Figure 1. LMA is presently developing the Engineering Unit.[2] The Engineering Unit will be the same as a flight generator, however, it will be heated with electric heaters that will simulate the plutonium heat source.

The Stirling system is an attractive alternative to Radioisotope Thermoelectric Generators (RTGs) due to the system efficiency of over 20 percent. This reduces the amount of plutonium required for a given power level by a factor of four or greater compared to thermoelectric generators. Past studies have shown that the SRG will also be lower mass for a given power level compared to the thermoelectric option.

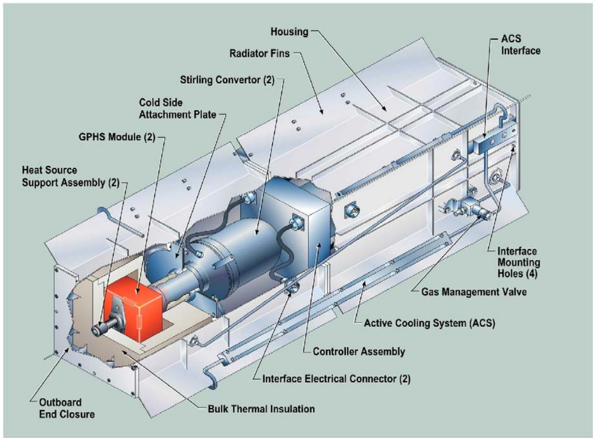

Figure 1. – Conceptual design of the SRG by LMA.

The TDC was developed previously by STC under contract to DOE.[3] STC is presently a subcontractor to LMA as the generator is being developed. There have been a total of 16 TDC's built by STC to date. GRC has six of the TDC's in the Stirling Research Laboratory; four that were purchased for in-house testing and two that are being tested for LMA. TDC's #5 through #8 have been proven to be rugged and reliable as they have been used for a wide range of tests. TDC's #13 and #14 have been put on test for LMA at GRC in support of the SRG project. The TDC's #13 through #16 are referred to as flight prototype units since they were built under the STC Quality Assurance (QA) system that includes 100 percent inspection. The build of #13 through #16 exercised the STC QA system in preparation for the build of future flight units.

NASA GRC is providing technical consultation for the development effort based on experience in Stirling technologies that dates back to the mid-1970's, including both kinematic and free-piston designs. The GRC supporting technology effort is a suite of tasks that includes in-house testing and evaluation of Stirling convertors, controllers and linear alternators, characterization of key metallic and non-metallic materials, structural analysis including heater head life assessment, electromagnetic interference/electromagnetic compatibility, and reliability analysis.[4]

IN-HOUSE TESTING

GRC has been operating TDC's in the Stirling Research Laboratory since October of 2000. Initially, TDC's #5 and #6 were put on test, and then TDC's #7 and #8 began operation in March of 2001. TDC's #5 through #8 have been used for a range of performance mapping tests, controller tests, transient tests, and some structural dynamic tests.[5–8] The TDC's were designed for long-life (>100,000 hours) through the use of non-contacting operation in a manner similar to that used on Stirling cryocoolers that are used in space. TDC's #5 through #8 have been used for very focused tests that require operation during the working day with the operator present. TDC's #5 through #8 have accumulated 2634 hours of operating at GRC, which is small compared to the design life, however, the types of the tests that have been conducted included daily starts and stops (controller, transient and steady state, structural dynamic) can be taxing on the hardware. The TDC's have proven themselves to be rugged and reliable throughout these tests.

Early tests of the TDC's that are being tested at GRC involved performance mapping.[9] These maps were generated with constant temperatures at the hot and cold ends of the cycle. This is commonly used in a research environment when the intent is to assess thermodynamic performance.

The SRG will make use of the General Purpose Heat Source (GPHS) module, which contains the plutonium heat source. The GPHS heat source will remain unchanged as the environment surrounding the SRG changes, less the 88 year half-life of the plutonium. The GPHS will therefore act like a constant flux heat source rather than a constant temperature heat source.

Performance mapping of the TDC's was repeated, with the heat source providing constant net heat input, and the temperatures allowed to seek equilibrium. Net heat is defined as the heat absorbed into the heater head from the heat source. This is gross heat minus the loss through the insulation to the surrounding environment. The performance measured was comparable to that measured with constant temperature mapping; only the transition from point-to-point was changed.

The previously mentioned tests were performed with the STC zener diode controller. In free-piston Stirling convertors, the frequency remains fixed with the amplitude of the piston varied to change the operation point. Piston amplitude is nearly proportional to output voltage of the linear alternator, and several Stirling convertor developers have used zener diodes as a means to control the output voltage. GRC has a controller that places a resistive load directly on the AC output of the linear alternator, rather than on the rectified, DC voltage as do the zener controllers. This controller is referred to as the 1st Generation Digital Controller. Performance mapping was repeated with the 1st generation controller. Of interest were the performance of the convertor and the harmonic content of the output current. As was expected, the performance was essentially unchanged. The harmonic content of the current was significantly reduced compared to the zener controller, indicating a path to reduced EMI if the need arose.

Tests were conducted to measure response of the TDC to large scale (step change) transients. These tests approached an electrical short on the output of the linear alternator. While this would never be planned in an application, a remote possibility exists of a short in the case of a rare event. Test apparatus was developed that could apply a fixed resistive load on the alternator after steady state operation had been achieved. The tests were conducted with lower and lower resistive values to observe the trend. During each test run, the current would spike as the resistive load was applied. This spike was measured and used to calculate the stress placed on the permanent magnets of the linear alternator and provide guidance on the subsequent test. It was found that the internal resistance of the linear alternator was sufficient to provide some measure of protection for a short circuit condition. While this may not be true for all free-piston Stirling linear alternators, it appears to be true for the TDC.

Tests were then conducted to characterize the start-up transient of the TDC. Since the TDC has non-contacting operation through the use of flexures, there is no contact even when the machine is not running. This eliminates friction from influencing the start-up. Each day, the start-up of the TDC would be measured with a different resistive load placed on the output of the linear alternator. The resistive load was varied from 250 to 650 ohms. As the heater head of the TDC was warmed, a point was reached when the convertor became unstable; that is the resonant free-piston Stirling was unstable and oscillation should begin. The fact that the convertor becomes dynamically unstable is not sufficient to guarantee start-up, therefore some random nature to the start-up transient does exist. With no friction to influence the start-up, a calculation can be made to determine what temperatures are required for the convertor to become unstable. It was found that in the laboratory environment, with no external forces applied to trigger oscillation, that start-up would typically occur within 30 ºC of the calculated temperature required for dynamic instability. Figure 2 shows the cross section of a laboratory TDC with the key parts labeled.

TDC's #13 and #14 were received at GRC in February of 2003. GRC was tasked to operate these TDC's in the role of Independent Validation and Verification (IV&V). TDC's #13 and #14 were installed on a test stand as shown in Figure 3. TDC's # 13 through #16 were fabricated at STC under their QA program that included 100 percent inspection. This QA program has been established in preparation for fabricating flight units. As such, these units are referred to as "flight prototypes." After the units had been assembled, it was jointly determined by LMA, STC and GRC that

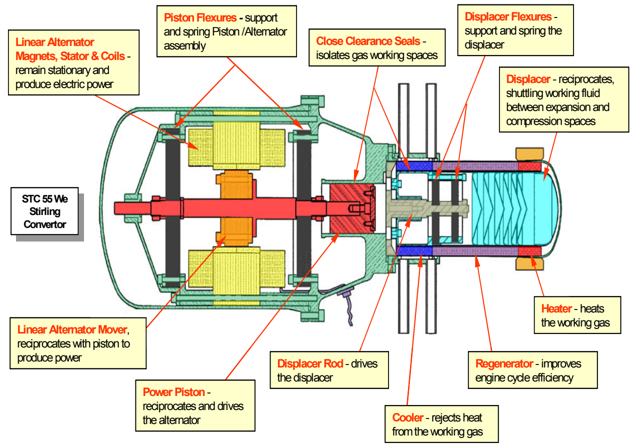

Figure 2. – TDC cross section including major components and functions.

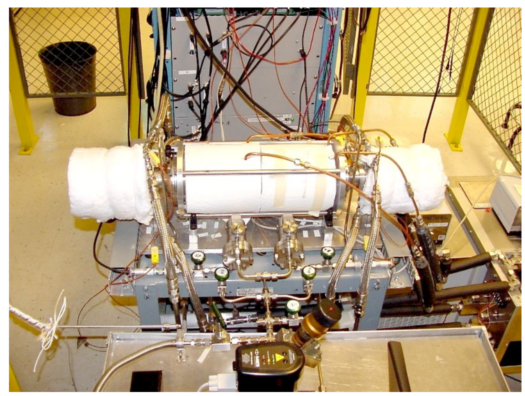

Figure 3. – TDC's #13 and #14 mounted in dual-opposed configuration.

vacuum bake out and a high purity helium working fluid fill would enhance the reliability of the TDC. This would normally be performed at the component and subassembly level, as is common practice in the processing of long life Stirling cryocoolers. Bake out of the full assembly would impose a limit to the bake out temperature based on the lowest temperature component. It was decided that vacuum bake out of the full assembly should be conducted to provide insight into the constituents being out-gassed, and the nature of the out-gassing process.

A bake-out chamber was constructed that would warm the TDC's, and a charge cart was developed that could evacuate the TDC's through the fill tube and analyze the evacuated gas during the bake-out. The bake-out chamber is shown in Figure 4, and the charge cart is shown in Figure 5. To maintain constant temperature, the bake-out chamber used a series of copper tubes and ethylene glycol circulating from a chiller with the temperature controlled to the desired set point by the chiller. The key components of the charge cart are a roughing pump, a turbo molecular pump, and a

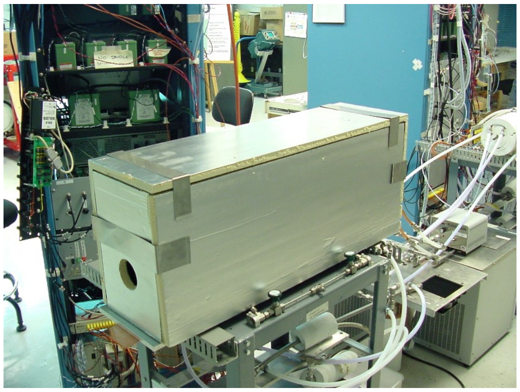

Figure 4. – Bake out housing on test stand.

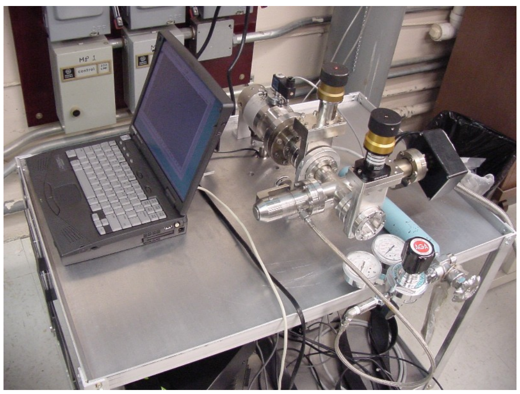

Figure 5. – Charge cart valves and data system with RGA and turbo pump below.

Residual Gas Analyzer (RGA). These components are connected on the charge cart with a series of volumes and valves to allow gas samples to be taken from the TDC's during the bake-out and evacuation. It also has the capability of taking a sample and analyzing the gas during full-power operation of the convertors. A data system recorded data from the RGA to indicate the progress during bake-out. After 200 hours the species being out-gassed was dominated by water vapor with some solvents present. The bake-out was terminated after 500 hours with the partial pressure of the water vapor at 1×10^{-6} Torr. While this is not as clean as a Stirling cryocooler might be, a Stirling power convertor is not limited by the presence of condensable gasses that foul heat exchangers in the coolers. It was felt that all useful information had been obtained in this convertor level bake-out without the benefit of component or subsystem bake-out. As the rate of reduction in the partial pressure of the water vapor lessened, a significantly extended time for the bake-out would have been required. A high purity helium fill was then introduced into the convertor for performance testing.

Table I. – Comparison of STC and GRC data for full power operation of TDC's #13 and #14.

	STC		GRC	
	Single	Single	Dual-Opposed	
Pressure (MPa)	2.52	2.53	2.52	2.53
Thot (ºC)	647.6	647.1	649.4	649.9
Tcold (ºC)	77.4	77.1	75.9	75.3
Talternator (ºC)	44.6	44.0	45.0	45.4
AC Power (W)	68.8	70.5	69.0	70.5
Efficiency (%)	28.2	27.8	27.6	25.9

A full power test was conducted to confirm the performance reported by STC. The data from this test are shown in Table I. The performance measured at GRC and STC were nearly identical with the difference being attributed to the slight variation in operating point. At STC, each TDC was operated as an individual unit, while at GRC the units were mounted in the dual-opposed configuration. The GRC configuration is the same as in the SRG and inherently forces the two units to operate at the identical frequency and with the same output voltage.

TDC's #13 and #14 have since been placed on extended operation. Operation continues 24 hours per day with a set of safety features built into the operation and data systems. The heart of the safety system is a Failsafe Protection Circuit that was developed at GRC. This circuit is capable or triggering a shutdown and placing a load on the linear alternator during the first half-cycle after a dynamic parameter has been sensed to be out or range. Extended operation commenced in June, 2003. Facility related issues initially prohibited continuous operation, however, 900 hours of operation has been accumulated as of August 10, 2003, and the convertors are presently operating 24 hours per day. The efficiency is slightly over 27 percent from net heat input to AC power output. The charging cart is taking gas samples twice per week to characterize the working fluid and detect out-gassed species. No measurable change in performance has been detected.

FUTURE TESTS

Future tests planned for TDC's #7 and #8 include measuring the frequency response of an operating TDC by placing a signal of varying frequency into the controller, and characterizing the operation with a wide range of tuning capacitors. The linear alternator is an inductive device, so a tuning capacitor is commonly used to keep the current in phase with the output voltage. This results in the load being applied to the power piston in phase with the velocity, which appears as pure damping on the motion. Changes in the tuning capacitor, and therefore the power factor, could have an impact on the conversion efficiency and the stability margin of the convertor.

A thermal vacuum test is planned that will operate TDC's #5 and #6 in a thermal vacuum tank to approximate the environment of deep space. The configuration of the test article is intended to be similar to the configuration of the SRG. Heat will be generated by a graphite electric resistance heater on each heater head that will simulate the GPHS module. The heat will be conducted to the Stirling heater head with a heat collector, or hot shoe, that functions the same as the heat collector in the SRG design. The test article will reject waste heat to the cold walls of the vacuum tank that will be chilled with liquid nitrogen. This will make use of radiator panels that reject the waste heat through radiation heat transfer. A thermal model is being prepared to predict the temperature profile of the system.

The thermal vacuum tank is being prepared for this test and is shown in Figure 6. The radiator panels for the test article are shown in Figure 7. STC is presently fabricating the heater heads with the heat collector and heat rejection flange. An image representing one of the TDC's prepared for the test is shown in Figure 8 with one radiator panel removed and the insulation cut away for clarity. The heat collector and the radiator panels will be instrumented; the data will be used for correlation with the thermal model. Operation in the thermal vacuum environment should begin in the fall of 2003.

Figure 6. – Thermal vacuum tank installation.

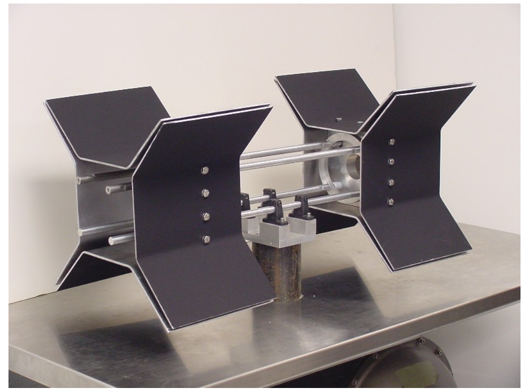

Figure 7. – Radiator panels for Stirling thermal vacuum test.

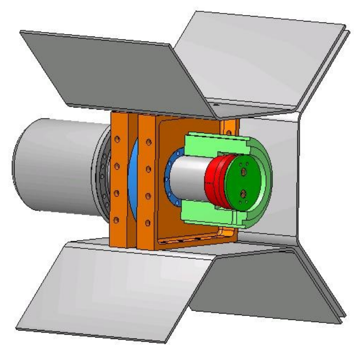

Figure 8. – TDC in configuration for the thermal vacuum test.

HEATER HEAD LIFE ASSESSMENT

The heater head of the TDC is viewed as one of the key components for long life. End of life of the heater head is defined as the onset of tertiary creep, which does not constitute a functional failure. The heater head is a thin-walled pressure vessel that must maintain the temperature differential of the thermodynamic cycle. The thin wall minimizes conduction losses and also reduces bending stresses as the hot-end grows relative to the cold-end. Inconel 718 (IN718) was selected for the heater head material because of the extensive material data base that exists to provide confidence of the design life, and the acceptable performance that was obtained. Creep data up to about 87,000 hours was recorded by the Oak Ridge National Laboratories (ORNL). The long-term durability of the heater head is being evaluated at GRC through a multi-faceted approach that incorporates both deterministic and probabilistic analyses, material tests, the ORNL data base, and benchmark tests of heater heads to calibrate the analytical models.[9] To date, only the uncertainties and variabilities of the IN718 heater head material has been considered in the probabilistic analysis. The analysis is now being enhanced to include the variability in geometric, pressure, temperature, and material property uncertainties into the life assessment. Furthermore, the SRG design places an axial preload on the heat collector, this altering the biaxial stress state of the thin wall. The analysis will also be enhanced to model this effect.

Two forms of tests are being used to support the durability analysis. Creep testing of the IN718 flight material is continuing at GRC with 7 active creep frames. The creep tests are being performed with thin samples, similar to the thickness used in the heater head, whereas the ORNL data was for thick samples.[10] The purpose of the ORNL test was to capture a wide range of IN718 samples, however, the space application tries to minimize the range. Scaling factors are being developed to account for the differences between the ORNL data and the GRC data. The temperatures of these tests range from 593 to 650 ºC. Over 166,000 hours of creep testing has been completed as of August 1, 2003.

A benchmark test has been initiated that will provide valuable data to validate the heater head durability analysis. The benchmark test places heater heads, and in some cases heater head mock-ups, under test with internal pressure and at temperature. A test rig holds the heater head to a base-plate. The heater head is pressurized from an external source to create stress in the thin wall. The heater section of the heater head is then heated with an induction heating system to simulate operation at temperature. Due to the characteristic of IN718 creep, the test does not attempt to accelerate the creep rate through the use of increased temperature. Acceleration is performed by increased stress on the wall through increased internal pressure. The test apparatus then measures creep of the heater head with high precision extensometers that measure radial growth. Critical to this test is accurate measurement of creep with the extensometers. A benchtop extensometer drift study has been completed with four instruments to ensure that there are no false readings that could be interpreted as creep. Two extensometers are used, rotated 90º from one another to check for any directional effects. A total of five test specimens are planned. The two initial specimens that will be tested have constant thickness thin walls. The first two tests are planned such that tertiary creep will be reached in one and three months. Two subsequent tests are planned that should reach tertiary creep in 6 and 12 months. These specimens have constant thickness walls rather than the tapered walls that are used in an actual heater head.

The result of these combined efforts will be a heater head life prediction that is presented in terms of Probability of Survival (POS) rather than the more common Factor of Safety (FOS) or margin. With relatively few heater heads that will be fabricated and even fewer that will be put into service, it is believed that the POS is a more valuable characterization of the design than the FOS.

MAGNET EVALUATION

Long-term magnet aging characterization continues on two types of FeNdB magnets. The Ugimag 40HC2 and 38KC2 magnets have now accumulated over 15,000 hours of aging while at 120 ºC and in a 6kOe demagnetization field. There has been no measurable loss of remanence in either magnet type within the 1 percent error or the measurement. Samples were taken at 200, 1,000, 2,000, 6,000, and 12,000 hours. These tests support the design of linear alternators for long-term performance without degradation.

Magnets from several other suppliers have recently been characterized and the results are being analyzed. These tests were for magnet strength and demagnetization resistance without any aging effects. Pending the analysis, these magnets may be evaluated in a short-term aging test. The short-term aging test lasts 200 hours, however, the test conditions used are more severe than for the long-term aging test. If the magnets are found to provide superior demagnetization resistance, they will then be placed on a long-term aging test along with the Ugimag magnets.

RELIABILITY

Based on the intended use of the SRG, as a power source for space science missions, there is the explicit requirement for high reliability. Missions to the outer planets have often been envisioned as being up to 14 years in duration. Achieving a high reliability design requires engineering and development; validating the high reliability may be less straightforward. GRC has recently initiated a reliability effort, part of which has been described previously.[11] The reliability effort has several components. The primary component is managed through the GRC Risk Management Office (RMO). RMO has assembled a team that includes Science Applications International Corporation (SAIC) and Sest, Inc. The purpose is to perform a reliability analysis of the TDC and then the SRG to quantify the mission reliability. In doing this, the team will identify the uncertainty in the estimated mission reliability, perform a reliability sensitivity study of the Stirling convertor and other system components, develop a plan for future analyses and testing to support the development, and develop guidelines to minimize the number of experiments that are required to demonstrate reliability of the generator. Sest has been involved in the probabilistic assessment of the durability of the heater head,[9] and they will now expand the analysis to include the entire Stirling convertor. This will involve not only the reliability of the individual components or subassemblies, but it will also include the interaction between components once the assembly has been completed. SAIC will integrate the Stiring convertor reliability model into a generator model that will include the structure, the controller, and thermal interfaces.

In parallel effort, GRC is performing analysis to assess the fasteners of the TDC. Failure Modes and Effects Analyses have commonly cited fasteners as a critical component in Stirling convertors. The GRC analysis will provide an independent, detailed assessment of the design. Unlike the aforementioned heater head analysis that resulted in a POS, this analysis will yield a design margin for each fastener when analyzed in a worst-case condition.

Cryocoolers have successfully overcome the challenges of acceptance for space missions as evidenced by the number or cryocoolers that are currently in flight. All except one of the long-life cyrocoolers that have been launched to date have been Stirling cryocoolers. Of the Stirling crycoolers, all except one have been flexure based machines like the TDC. A third reliability effort will make use of Sest and Swales, Inc to provide advice and guidance based on the lessons-learned in cryocooler development. In conjunction with this, a database of flight quality long-life cryocoolers is being developed at GRC to track relevant data that can be useful in determining the reliability these types of machines.

OTHER TASKS

Some organic compounds are present in the TDC, predominantly in the linear alternator. An initial review of the organics determined that the bond of the magnet to the linear alternator laminations was critical for reliability. The bond is made with 3M Scoth-Weld™ 2216 B/A Gray epoxy. Study of the cure kinetics has progressed and the characteristics are now well understood.[4] Short-term tests have been completed, and long-term durability testing is being planned to age the bond for up to three years in a helium environment.

Three-dimensional magnetostatic analysis of linear alternators was developed at GRC.[12] This analysis was validated in a test whereby the onset of demagnetization was accurately predicted. The analysis has more recently been used to determine the worst-case mechanical load that can be placed on the magnets. This load was then used to determine the test conditions for the bond that holds the magnet onto the laminations of the stator. A test will be started in late 2003 that will test the thermal-mechanical integrity of the magnet bond, under the analytically determined conditions.

Further validation of the magnetostatic linear alternator analysis requires data obtained from operating linear alternators. To acquire this data, a Linear Alternator Test Rig (LATR) has been installed in the lab. Initially, the LATR will be used to motor TDC linear alternators that are under test. The plan is to motor a test alternator in which the permanent magnets can be replaced. Prediction will be made for demagnetization and compared against measured data.

Structural dynamics and attention to the launch environment have been key areas of study at GRC. This application will have the Stirling convertors operating during the launch sequence. There have been four tests completed at GRC and reported in the past.[5–8] The plans currently call for a combination of analyses ant tests. Details of the tests must be worked into the overall SRG project to consider hardware availability.

ADVANCED TECHNOLOGY

An advanced Stirling technology effort continues at GRC in parallel with the transition to flight. The purpose is to develop the technologies necessary to for lower mass and/or improved performance. The SRG is estimated to have specific power of approximately 4W/kg. Analysis has shown that this can be doubled with the use of advanced, yet near-term technology. A roadmap has been proposed with a second-generation generator with reduced mass and a third-generation generator with increased performance.[4] The improvements needed for the second-generation convertor will be through mass improvements that make use of lightweight Stirling convertor designs, improvements in the fraction of Carnot efficiency that can be obtained, increased in the Carnot efficiency, and reduced mass controllers.

One example of a low mass design is presently under development.[12] Sunpower, Inc., Athens, Ohio, has completed the design of a low mass Stirling convertor under a NASA GRC Phase I Small Business Innovative Research (SBIR) contract. The SBIR Phase II contract was awarded in 2002 and the development began in

September, 2002. A prototype of the low mass Stirling convertor has been fabricated and testing has been initiated.

An increase in the fraction of the Carnot efficiency that can be obtained will come by the reduction is losses. While the optimization of a design minimizes the losses, it can only do so based on our current understanding of the losses. Multi-dimensional cycle analysis is being performed on the TDC to determine where there might be a reduction in the internal losses. The analysis makes use of commercial code, CFD-ACE, developed by CFD Research Corporation. This effort is being closely coordinated with multiple regenerator research efforts. A team led by Cleveland State University (CSU) is developing multi-dimensional Stirling cycle analysis code under a GRC grant. CSU also leads a team that is investigating potential improvements in regenerators through a grant from DOE-Golden. CSU has recently been awarded a research grant through the NASA Radioisotope Power Conversion Technology NASA Research Announcement (NRA). All of these efforts have the goal of increasing the fraction of Carnot efficiency that can be obtained.

The selection of IN718 for the TDC heater head allows operation for long-life application up to approximately 650 ºC. This can be traded somewhat to gain increased operating temperature at the cost of life. The use of a higher temperature heater head will improve the Carnot efficiency that is available. Within the class of nickel-based superalloys there are some choices that could allow operation as high as 870 ºC. In developing the material, the trade that gains high temperature capability often makes joining more difficult. The ability to use higher temperature heater heads is generally a result of improved joining technology. GRC is currently studying the alloys available and the joining technologies. The selection of the alloy must consider the long-term stability of the material at elevated temperatures while under stress.

As mentioned earlier, the Stirling Research Laboratory at GRC has made use of the STC zener diode controller and the GRC 1st generation digital controller in past tests. A 2nd generation digital controller has been developed at GRC that will hold the output voltage constant, regardless of the external load. The 1st generation controller did not maintain constant voltage if an end-user were to apply a load. The 2nd generation controller should provide an improvement in this respect. A Pulse Width Modulated (PWM) controller has been designed and fabricated that will eliminate the need for a tuning capacitor on the output of the alternator. Advanced versions of this controller are currently being designed and analyzed. These advanced controllers will be minimize the parts count, improve efficiency, and perform functions other than simple control. The goal is to combine functions such as vibration reduction and synchronization features into the controller by manipulating the current that flows through each alternator, including higher harmonics in response to a range of external signals.

CONCLUDING REMARKS

A range of efforts continue at GRC in support of the transition to flight along with the development of advanced technologies. Some of the activities that support the transition to flight were highlighted including in-house testing, heater head life assessment, permanent magnet evaluation, and reliability analysis. The purpose of these tasks is to support the successful development of the SRG. A complementary advanced technology effort was described that is intended to provide the technologies necessary for advanced generators. Performance improvements are being sought in terms of increased fraction of Carnot that can be obtained, and increasing the Carnot efficiency itself.

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13. ABSTRACT ***(Maximum 200 words)***
The Stirling Radioisotope Generator (SRG) is currently being developed by Lockheed Martin Astronautics (LMA) under contract to the Department of Energy (DOE). The generator will be a high efficiency electric power source for NASA Space Science missions with the ability to operate in vacuum or in an atmosphere such as on Mars. High efficiency is obtained through the use of free-piston Stirling power conversion. Power output will be greater than 100 watts at the beginning of life with the decline in power largely due to the decay of the plutonium heat source. In support of the DOE SRG project, the NASA Glenn Research Center (GRC) has established a technology effort to provide data to ensure a successful transition to flight for what will be the first dynamic power system in space. Initially, a limited number of areas were selected for the effort, however this is now being expanded to more thoroughly cover key technical issues. There is also an advanced technology effort that is complementary to the near-term technology effort. Many of the tests use the 55-We Technology Demonstration Convertor (TDC). There have been multiple controller tests to support the LMA flight controller design effort. Preparation is continuing for a thermal/vacuum system demonstration. A pair of flight prototype TDC's have been placed on continuous operation. Heater head life assessment continues, with the material data being refined and the analysis moving toward the system perspective. Magnet aging tests continue to characterize any possible aging in the strength or demagnetization resistance of the magnets in the linear alternator. A reliability effort has been initiated to help guide the development activities with focus on the key components and subsystems. This paper will provide an overview of some of the GRC technical efforts, including the status, and a description of future efforts.

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