



# Final Results for the GRC Supporting Technology Development Project for the 110-Watt Stirling Radioisotope Generator (SRG110)

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## **Abstract**

From 1999 to 2006, the NASA Glenn Research Center (GRC) supported the development of a high-efficiency, nominal 110-We Stirling Radioisotope Generator (SRG110) for potential use on NASA missions, including deep space missions, Mars rovers, and lunar applications. Lockheed Martin (LM) was the system integrator for the SRG110, under contract to the Department of Energy (DOE). Infinia Corporation (formerly Stirling Technology Company) developed the Stirling convertor, first as a contractor to DOE and then under subcontract to LM. The SRG110 development has been redirected, and recent program changes have been made to significantly increase the specific power of the generator. System development of an Advanced Stirling Radioisotope Generator (ASRG) has now begun, using a lightweight, advanced convertor from Sunpower, Inc. This paper summarizes the results of the supporting technology effort that GRC completed for the SRG110. GRC tasks included convertor extended-duration testing in air and thermal vacuum environments, heater head life assessment, materials studies, permanent magnet aging characterization, linear alternator evaluations, structural dynamics testing, electromagnetic interference (EMI) and electromagnetic compatibility (EMC) characterization, organic materials evaluations, reliability studies, and development of an end-to-end system dynamic model. Related efforts are now continuing in many of these areas to support ASRG development.

## **Introduction**

From 1999 to 2006, the NASA Glenn Research Center (GRC) supported the development of a high-efficiency, nominal 110-We Stirling Radioisotope Generator (SRG110) for use on potential NASA Space Science missions (Thieme, 2005). Lockheed Martin (LM) was the system integrator for the SRG110 (Cockfield, 2002), under contract to the Department of Energy (DOE). Infinia Corporation (formerly Stirling Technology Company) developed the Stirling convertor, first as a contractor to DOE and then under subcontract to LM. The SRG110 development has now been redirected, and recent program changes have been made to significantly increase the specific power of the generator. System development of an Advanced Stirling Radioisotope Generator (ASRG) has now begun, using a lightweight, advanced convertor from Sunpower, Inc.

This paper summarizes the results of the supporting technology effort that GRC completed for the SRG110. GRC tasks included convertor extended-duration testing in air and thermal vacuum environments, testing for controls development, heater head life assessment, materials studies, permanent magnet aging characterization, linear alternator evaluations, structural dynamics testing, electromagnetic interference (EMI) and electromagnetic compatibility (EMC) characterization, organic materials evaluations, reliability studies, fastener evaluation, and development of an end-to-end system dynamic model. Related efforts are now continuing in many of these areas to support ASRG development.

## **The 110-Watt Stirling Radioisotope Generator (SRG110)**

Development of the Technology Demonstration Convertor (TDC) for a space radioisotope power system was begun in 1998 by Infinia, under contract to DOE. At that time, a Stirling power system was considered a backup to Alkali Metal Thermal Electric Conversion (AMTEC). The TDC was designed to

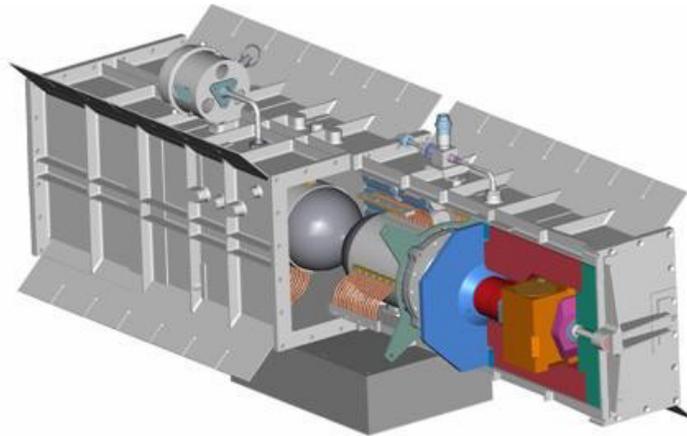


Figure 1. —SRG110 generator with dual-opposed Stirling converters.

convert heat from one general purpose heat source (GPHS) module to electric power and used flexures to achieve non-contacting operation. A power output of over 55 W and efficiency greater than 27 percent (heat input to AC electric power output) were achieved. The TDC had a mass of about 6 kg, with mass reduction expected during flight development.

After AMTEC development was discontinued in 1999, a joint DOE/NASA/industry team evaluated the readiness of Stirling power conversion technology to transition into formal flight development. A 3-month study was conducted that looked at the following key issues: (1) launch load capability, (2) EMI/EMC, (3) performance mapping, (4) radiation tolerance, (5) controller design, (6) failure modes effect and criticality analysis (FMECA) of the Stirling convertor, and (7) fault-tolerant system configuration. Based on the findings of this Technology Readiness Assessment (Furlong and Shaltens, 2000), development of a 100-W class Stirling radioisotope generator (SRG110) was authorized.

LM was selected as the system integration contractor, and development of the SRG110 began in May 2002. The designs were initially for use in deep space; however, a modification was later issued to include operation on the surface of Mars. The LM design enclosed two GPHS modules and two Stirling converters inside a beryllium housing that acted as structure and radiator (Cockfield and Chan, 2002). The final design resulted in a projected 116-W power output at beginning-of-mission and 101-W power output after 14 years in space, with a mass of 32.5 kg and specific power of 3.6 W/kg. Figure 1 shows the final design of the SRG110.

## **GRC Supporting Technology Development for the SRG110**

In 1999, a technology effort was started at GRC to address many of the key aspects of the Stirling convertor development and its eventual integration into a generator. Since the technology effort was to support flight development, all of the tasks ultimately contributed to life and reliability. The results of the various tasks completed between 1999 and 2006, as part of this effort, are summarized below. Various project summaries are included in Schreiber (2006a), Schreiber and Thieme (2004), Thieme and Schreiber (2000; 2005), and Thieme, Schreiber, and Mason (2002). GRC also provided technical consulting for the convertor development under Space Act Agreements with DOE.

### **Extended-Duration Convertor Testing**

Free-piston Stirling converters have been operated at GRC since the late 1970s for a diverse set of applications, including residential heat pumps, terrestrial power generation, nuclear space power, and radioisotope space power. To support the SRG110 development, GRC tested a total of 10 converters built

by Infinia. TDCs numbers 5 and 6 were received by GRC in September 2000. They were early developmental convertors and were first used for a wide range of tests, including performance characterization and a variety of controller tests. All of these tests were relatively short-term, focused tests that were conducted in the presence of a test engineer. TDCs numbers 7 and 8 were delivered to GRC in March 2001 and were similarly used for a range of short-term tests. Following the selection of LM as the SRG110 system integration contractor, TDCs numbers 13 and 14 were sent to GRC for extended operation testing in February 2003, as were TDCs numbers 15 and 16 in February 2005. These TDCs were the first convertors built by Infinia under the Quality Assurance Program that was being developed in preparation for the eventual fabrication of flight hardware. TDCs numbers 13 and 14 were put on extended operation in June 2003; testing began on TDCs numbers 15 and 16 in March 2005. Finally, a brief performance test was run on a pair of convertors, SES numbers 1 and 2, that were built for use in the SRG110 Engineering Unit. A summary of convertor testing at GRC is given by Schreiber (2006b).

A pair of dual-opposed TDCs is shown on a test station at GRC in figure 2. The test station includes a rack with the data system and controls, the test stand, the cooling system, and the gas management system. The data system is based on LabVIEW (National Instruments) commercial hardware and software, and is used to monitor operation and record data. The software was developed for unattended operation to include automatic shutdown of the convertors in the event of a failure or detection of an out-of-range reading in a monitored operating condition. If a loss of utility power is sensed, the test stand can be operated by an Uninterruptible Power Supply for 5 min before a controlled shutdown is initiated. Additional safety is provided by hard-wired shutdowns that monitor both steady state and dynamic parameters (including piston positions and accelerometers) and do not rely on the LabVIEW software.

A gas charging system was developed that is used to monitor the emissions from the convertor during bake out, charge the convertors with high-purity helium with measured composition for operation, and monitor the composition of the working fluid during operation. The system makes use of a Residual Gas Analyzer (RGA) for analysis of gas composition. This capability was developed to help meet the goal of extended operation, to seek and measure any changes that may occur over time.

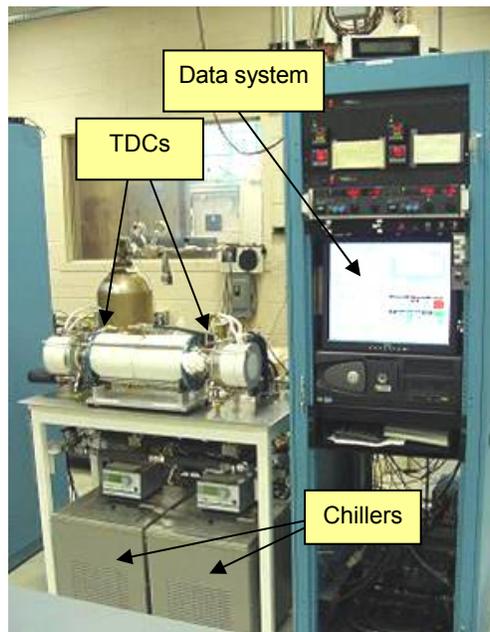


Figure 2.—A pair of TDCs on a test stand at GRC under extended operation test.

### ***Extended Operation of TDCs Numbers 13 and 14***

The test facility and testing of TDCs numbers 13 and 14 are discussed by Roth, Schreiber, and Pepper (2004). A 500-hr vacuum bake out was first conducted on TDCs numbers 13 and 14 to remove any moisture or other sources of oxygen that would allow the stainless steel regenerator to oxidize at the operating temperature. The convertors were maintained at approximately 80 °C while the turbomolecular vacuum pump evacuated the internal volume. The total pressure was measured at  $4 \times 10^{-6}$  torr, with about  $1 \times 10^{-6}$  torr of water. A small amount of isopropyl alcohol was also detected by the RGA, which was believed to originate from cleaning during manufacturing.

Early in the extended operation test, there was a loss of about 3 psi of helium per week from the nominal fill pressure of 365 psig. By October 2003, it was apparent that the efficiency had decreased slightly, from about 27.2 to 27.1 percent on TDC number 13 and from about 26.7 to 26.5 percent on TDC number 14. At the same time, the gas analysis of the working fluid was showing increased concentrations of argon and nitrogen. It was hypothesized that helium was permeating outward through the o-rings and that ambient atmosphere was permeating inward. The source of argon was believed to be pockets, formed by blind fastener holes, which filled with argon during insulation loss tests. The source of nitrogen was thought to be the ambient atmosphere, with the oxygen being consumed by oxidation of the stainless steel regenerator and thus no oxygen appearing in the gas analysis. The consumption of oxygen by the regenerator was also hypothesized to be the reason for the slight decrease in efficiency.

To resolve this, purge rings were installed (after 2,800 hr of operation) around the bolted flanges that would provide a controlled inert atmosphere outside the o-rings, using argon to cover the o-ring flanges. The choice of argon was based on an original goal of 5,000 hr of operation and calculations that showed that the concentration of argon that would result from this amount of operation would not affect the thermodynamic performance to a measurable extent. The results were immediate, with the concentration of nitrogen remaining constant and the concentration of argon increasing. This result was consistent with the hypothesis that the gasses were permeating through the o-rings during operation and that the oxygen was being consumed by the regenerator. The test was then extended in duration, and the argon purge was changed to helium after 6,500 hr of operation. This resulted in the argon and nitrogen concentrations staying constant and even decreasing slightly over time. As operation continued with permeation of oxygen into the convertor eliminated, the performance became level with no change in convertor efficiency, even though it is believed that the regenerator suffered damage during the early operation.

After about 19,000 hr of operation, TDCs numbers 13 and 14 were shut down for hermetic seal welding of the bolted flanges. When the heater heads and the pressure vessels were removed, a noninvasive inspection was performed. The inspection, conducted by a team from GRC and Infinia, was visual and had very limited ability to take samples. The inspection team looked specifically for indications of wear on surfaces, particles that may have resulted in wear, debris from the regenerator, accumulation of particles on the magnets of the linear alternator, and visual evidence of aging of the organics in the linear alternator. The inspection found no evidence of wear during operation or debris. Slight markings that were observed were generally attributed to the original build process. Prior to welding, the TDCs were operated for a short period following inspection to verify that the inspection did not alter the operation in any way.

Hermetic laser seal welding was completed by the Edison Welding Institute (EWI) of Columbus, Ohio in January 2006. The TDCs were then tested for a short period at a low-temperature operating point to verify proper performance. Operation was nominal and generally in agreement with the pre-weld operation. The TDCs were then shut down for bake out to allow for a high purity fill with helium. This bake out lasted only 125 hr and resulted in a total pressure of  $4.5 \times 10^{-7}$  torr, with the dominant species being water. TDCs numbers 13 and 14 were then returned to full-power operation.

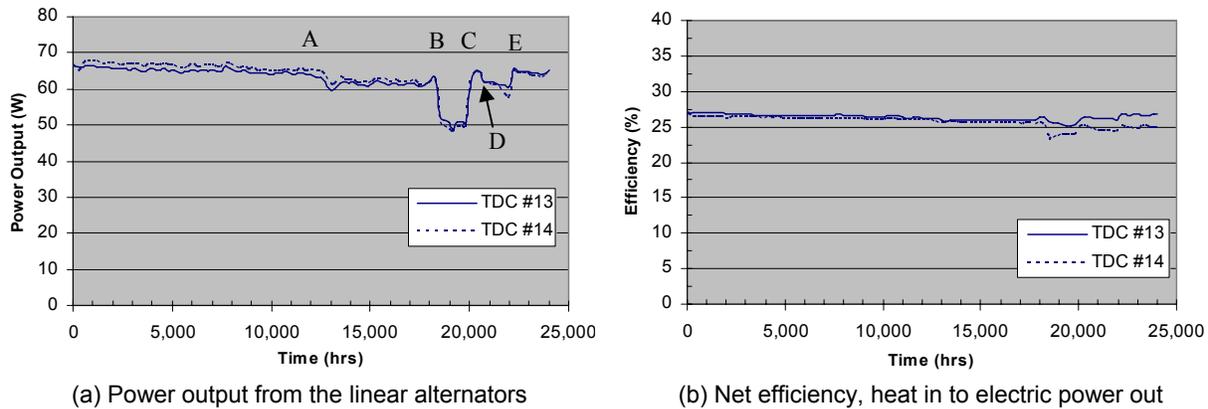


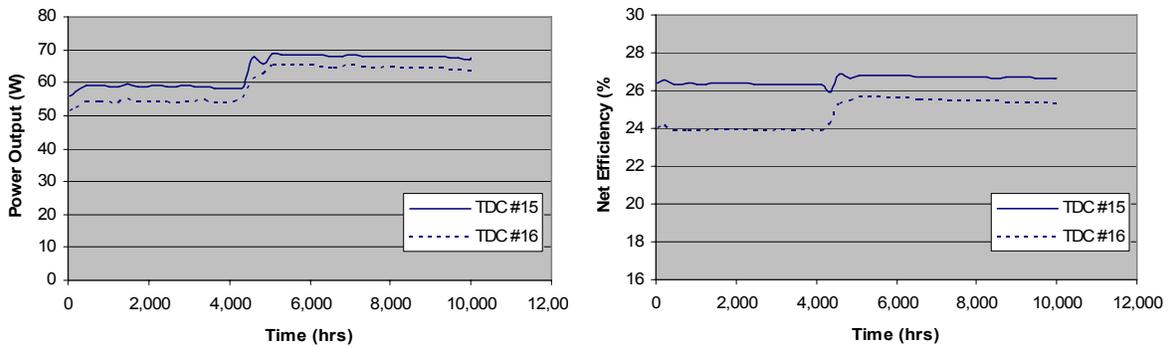
Figure 3.—Performance data from TDCs numbers 13 and 14 through 24,000 hr of operation.

Test data from TDCs numbers 13 and 14 are shown in figure 3. The measured power output was corrected, using a linear correction proportional to the difference between the measured and design mean pressures, to account for changes in the mean operating pressure prior to hermetic sealing. The slight degradation in conversion efficiency can be seen through the first 5000 hr of operation. The transient in performance around 8000 hr is a result of the move to a new test facility causing some disturbance to the insulation and changes in the coolant flow rate due to modifications in the cold-end plumbing. The change in performance at 12,000 hr (A) was due to a change in coolant composition (pure ethylene glycol to 50/50 mixture with water and then back to pure ethylene glycol). The transient at about 18,600 hr (B) was in preparation for hermetic seal welding, with a return to full operating conditions at about 20,000 hr (C). Changes noted at 20,600 hr (D) are due to failed heaters on both convertors and a subsequent adjustment in the heater temperatures; all heaters were replaced on both convertors at about 22,000 hr (E). To date, over 24,200 hr of extended operation have been completed on TDCs numbers 13 and 14, with over 5,000 hr since the hermetic seal weld. No failures or otherwise anomalous operation have been found that could be attributed to the TDCs. The extended operation test is continuing as part of the ASRG effort.

#### ***Extended Operation of TDCs Numbers 15 and 16***

Operation of TDCs numbers 15 and 16 was initially limited to a low-temperature operating point of 500 °C hot-end temperature, since these convertors had not been baked out to eliminate residual oxygen. In October 2005, the convertors were shut down for hermetic sealing, with approximately 4400 hr accumulated. The hermetic seal welding was completed at EWI, and TDCs numbers 15 and 16 were returned to operation at GRC in December 2005. Convertor performance after the weld was found to be nominally the same as before the weld. The convertors were then shut down for bake out to remove any residual oxygen. Bake out lasted approximately 250 hr and reached a total pressure of  $2.3 \times 10^{-7}$  torr, more than an order of magnitude less than had been achieved in 500 hr with TDCs numbers 13 and 14 in their original bake out. It is believed that this more rapid bake out to lower levels of pressure is the result of the low-temperature operation.

TDCs numbers 15 and 16 were then filled with high-purity helium. Nominal operation was achieved at the low-temperature operating point, so the temperatures were increased to the design point of 650 °C hot-end temperature and 80 °C cold-end temperature. To date, over 10,200 hr of extended operation have been completed on TDCs numbers 15 and 16, and the convertors have been operating continuously for about the last 4,000 hr. Test data from TDCs numbers 15 and 16 are shown in figure 4. The data show flat-line performance in both power and efficiency for both convertors. There is a slight difference in the performance, which can likely be attributed to tolerances in the clearance seals. The transient at about



(a) Power output from the linear alternators (b) Net efficiency, heat in to electric power out

Figure 4.—Performance data from TDCs numbers 15 and 16 through 6000 hr of operation.

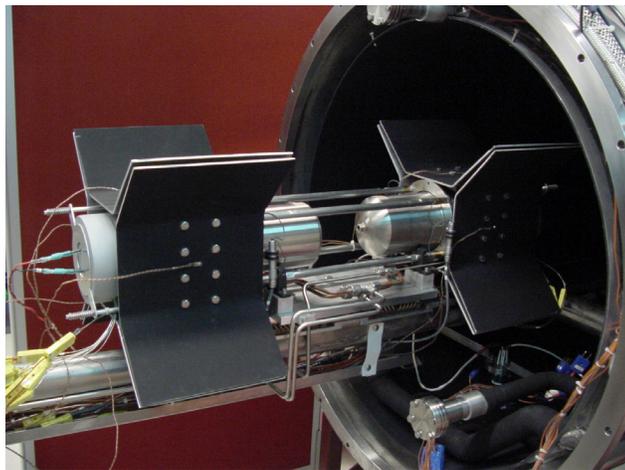


Figure 5.—TDCs numbers 5 and 6 configured for thermal vacuum extended operation test.

4,400 hr is the shutdown and restart for hermetic seal welding. The small transient at about 4,500 hr is the shutdown and restart for bake out. The transient near 5,000 hr is an adjustment in the operating condition, following replacement of all heaters on both converters due to two heater failures. No failures or otherwise anomalous operation have been found that could be attributed to the TDCs. The extended operation test is continuing as part of the ASRG effort.

### ***Extended Operation of TDCs Numbers 5 and 6 in Thermal Vacuum***

Following the early testing with TDCs numbers 5 and 6, a decision was made to put these converters into extended operation in a thermal vacuum environment that would simulate operation in deep space. The test article, as installed in the vacuum facility at GRC, is shown in figure 5. New heater heads were fabricated with prototypical heat collectors similar to those that were designed for transporting heat from the GPHS modules to the Stirling converters in the SRG110. Borelectric (GE Advanced Ceramics) heaters were clamped to the heat collectors to simulate the GPHS modules. The heat collectors were instrumented with thermocouples to characterize the temperature distribution during operation. The heater head was fabricated with a nickel flange brazed to the heat rejection area to conduct waste heat to the radiator panels. The nickel flanges were sandwiched between copper plates to enhance net conductivity. The operating temperatures were determined by the conduction and radiation paths inherent in the hardware. Two sets of radiator panels were made to allow adjustment of the cold-end temperature during operation (Oriti, 2005).

TDCs numbers 5 and 6 were initially operated in the thermal vacuum facility in November 2004. Nearly 1,000 hr of operation were first completed at a 500 °C convertor hot-end temperature. As the temperature was increased to slightly more than 600 °C, it was found that full-temperature, full-power operation was not possible due to the temperature of the pressure vessel, and it was evident that the alternator temperature was nearing the temperature limit of the permanent magnets. An analysis indicated that the desired thermal conditions could be reached with larger radiator panels installed on the cold flanges and with the emissivity of the pressure vessel increased by surface treatment. The experiment was shut down at about 4,300 hr, the larger radiator panels were installed, and the pressure vessel was covered with Kapton (DuPont) tape to increase the emissivity. With the hot-end temperature at 500 °C, the resulting cold-end and pressure vessel temperatures indicated that acceptable temperatures would result for a hot-end temperature of 650 °C. Therefore, the TDCs were baked out for a high-purity fill with helium. After 5,200 hr of operation in thermal vacuum, the temperatures were increased to the design point of 630 °C hot-end temperature and 70 °C cold-end temperature, with a resulting power output of about 63 W per convertor.

TDCs numbers 5 and 6 completed 10,016 hr of extended operation in thermal vacuum in August 2006. The test was ended at this time to prepare for thermal vacuum testing of the lightweight, advanced convertors. Once the thermal operating conditions were resolved, performance over the last 4000 hr was constant. All of the issues encountered with operating TDCs numbers 5 and 6 in thermal vacuum originated from extended operation of the thermal vacuum facility itself or from the supporting control systems. None originated from the TDCs themselves.

### ***Controller Development***

As part of the GRC technology development effort, tests have been performed to investigate the characteristics of various controller architectures. Initial performance tests used the zener-diode controller that was developed by Infinia. This controller was found to be ideal for performance mapping of convertors in a laboratory environment; however, it leads to significant harmonic content in the output current from the linear alternator. A first-generation digital controller was developed at GRC that significantly reduced the harmonic content of the current and maintained the near-unity power factor of the output. This controller used digital logic to apply an analog resistive load to maintain control of the convertor. Little difference was found in convertor performance when operating on the two controllers. The digital controller allowed the alternator output voltage to vary slightly as the power output changed; a second-generation digital controller was developed that maintained constant output voltage. Tests were also conducted in direct support of LM controller development. These included tests to explore the limits of operation with off-nominal tuning capacitors and unbalanced tuning capacitors between dual-opposed convertors. DC node and frequency response tests were also completed. Finally, an active power factor correction controller was under development at the end of the SRG110 project. This controller uses power electronics to eliminate the heavy and large tuning capacitors needed in the other controllers.

An end-to-end System Dynamics Model (SDM) was developed at GRC and was used for controller development by both GRC and LM. 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. An interface with the Sage Stirling code was added to improve predictions of Stirling cycle thermodynamics. The SDM and examples of studies completed with the SDM are described by Lewandowski and Regan (2004) and Regan and Lewandowski (2004).

### **Heater Head Life Assessment**

The heater head is a critical component in achieving long life in Stirling convertors where all wear mechanisms eliminated by design. The heater head is known to have the potential to creep over time,

depending on specifics of the design and the operating conditions. Inconel 718 (IN718) was selected for the heater heads in the SRG110. An approach was developed at GRC to characterize the long-term durability of the heads based on probabilistic analysis, material testing, and an existing Oak Ridge National Laboratories database with creep data up to 87,000 hr (9.9 yr). Initial creep tests were completed to optimize the grain size, since larger grains that normally provide low creep rates resulted in too few grains through the thin walls (Bowman, 2001). Creep testing was conducted on two purchases of IN718, with the maximum time on a single test specimen being 43,700 hr, as of September 2006, at a stress level of 414 MPa (60 ksi) and a temperature of 593 °C. Structural benchmark tests were used to factor in the true biaxial stress state and to validate the analysis. The analysis was based on probabilistic techniques that project Probability-of-Survival (PoS) of the heater head over a given life. This technique considered uncertainties in the material properties, heater head geometry, and convertor operating conditions. End-of-life was defined as the onset of tertiary creep, which occurs at about 70 percent of the time to creep rupture for this material. Early life assessment efforts led to a significant increase in the heater head wall thickness in the regenerator area. Life assessment calculations based on the revised design showed a heater head life of 188,000 hr (21.5 yr) for a PoS of 99.9 percent and 116,000 hr (13.2 yr) for a PoS of 99.99 percent (Shah, Halford, and Korovaichuk, 2004). A recent update to this calculation, factoring in additional GRC IN718 creep data on the two heats of material, showed a heater head life of 218,000 hr (24.9 yr) for a PoS of 99.9 percent and 140,000 hr (16.0 yr) for a PoS of 99.99 percent. Change in internal volume of the pressure boundary is negligible even at the maximum allowable creep.

Four accelerated structural benchmark tests of heater head pressure vessels have been completed. The results are summarized in table 1. The tests shown as Bitec1, 2, and 3 were done on thin-walled (0.38 mm thick) pressure vessels made by Bitec Sample Machining, Inc. of Dayton, Ohio, specifically for these tests. The reduced wall thickness and increased pressure levels (relative to the Stirling convertor wall thickness and operating pressure) were used to accelerate the testing and were chosen to reach the onset of tertiary creep in 1- to 3-month time periods. A fourth accelerated test was completed on a tapered-wall pressure vessel, STC209, built by Infinia with the same geometry as used in the SRG110 convertor. Two non-accelerated tests with tapered-wall pressure vessels, STC206 and STC212, were run at the convertor design operating pressure. STC206 included a brazed heat collector similar to that used in the SRG110 to transfer heat from the GPHS to the Stirling convertor. All tests were run at 650 °C in the gage area at the hot end of the regenerator, which is the primary area of interest for creep. These tests are discussed by Krause and Kantzos (2006) and Krause, Kalluri, and Bowman (2007).

TABLE 1.—SUMMARY OF HEATER HEAD STRUCTURAL BENCHMARK TEST RESULTS.

Benchmark test type		Accelerated				Non-accelerated	
Test article		Bitec1	Bitec2	Bitec3	STC209	STC206	STC212
Predicted	Creep rate	high	mod. high	mod. high	moderate	very low	very low
	Time to tertiary (days)	22	67	67	moderate	high	high
Observed	Creep rate	very high	high	v. v. high	low	very low	low
	Test duration (days)	30	59	25 (rupture)	131	235 (ongoing)	330 (ongoing)
	Creep rate anisotropy	1.2:1	3:1	2:1	1:1	5.5:1	20:1

The test results showed that the average response for the SRG110-design test articles is in agreement with predicted creep strain rates, based on the high scatter common in experimental creep results. However, the testing revealed significant variations in creep rate around the circumference of the measured gage area; this condition, if not alleviated, would reduce the calculated median heater head life. The three Bitec test articles used for accelerated testing produced less anisotropy but higher than expected creep strain rates. An investigation of this found a significant creep response dependency on the cooling

rate used during these test articles' less-controlled heat treatment. It is theorized that variable and lower than desired cooling rates resulted in out-of-specification formation of precipitates, causing increased creep rates compared to those predicted and possibly some creep rate anisotropy. A post-test microstructural evaluation is expected to be completed soon on the STC212 specimen with the highest anisotropy to see if precipitate differences may be the explanation. Earlier tests had ruled out any significant impacts of circumferential temperature variations and measurement error. Even with the variations seen in the benchmark testing, results for all six benchmark tests fall within the 99.9 percent probability-of-survival curve (approximately three standard deviations) that was based on uniaxial creep testing and related stress and secondary creep rate.

Axial and lateral load testing were also completed at GRC on a heater head test specimen supplied by Infinia, in support of LM and Infinia quantifying the heater head cold-end design margins. The design temperature gradient was applied to the cold end of the heater head. The maximum lateral load, where the reaction modulus weakened very significantly, was about five times higher than the required test verification load. The observed final failure mode was inelastic buckling of the thin heater head wall on the compressive-stress side. The test results compared well with pre-test predictions.

### **Materials Studies**

The regenerator is a matrix of sintered random metal fibers. This has posed a concern with respect to reliability if some fibers could become detached from the matrix during operation, possibly traveling to a critical location that cannot tolerate the physical presence of the fiber. Known cases of fiber shedding during convertor testing can be attributed to improper processing of the regenerator (sintering and/or cleaning), or improper operation of the convertor (oxidation). The sintering process of the regenerator matrix was optimized for strength by varying time and temperature. Sintering schedules were evaluated by optical inspection, tensile tests, and measuring the amount of fibers that were shed when the regenerator was cleaned in an ultrasonic cleaner. It was found that regenerators could be made with no fibers being shed under continued testing, by using an optimized sintering process followed by a controlled cleaning process.

The oxidation resistance of stainless steel regenerators, as typically used in Stirling convertors, was investigated by GRC and Infinia. Processed and unprocessed regenerator material and regenerators tested in various convertors were studied. Oxidation effects were evaluated in both air and helium environments. Possible alternate materials with higher oxidation resistance were also studied, and one was selected to replace the stainless steel material for the regenerator. A further effort looked at the need for coatings on the displacer radiation shields to maintain a stable, low-emissivity surface over the life of the convertor. The level of cleanliness of the flight convertors, including the helium fill, and any possible outgassing of organic materials are factors in minimizing any oxidation effects on these components.

GRC and Infinia collaborated to verify that the heater head brazing and heat treating procedures that were developed on laboratory samples would yield the desired microstructure in the final heater heads. Infinia fabricated and processed two heater heads and included witness coupons in various locations of the brazing furnace. These coupons were first examined at GRC to document their initial microstructures. After processing at Infinia, the heater heads and coupons were analyzed by GRC. The study showed that no grain growth had occurred during the processing and that the precipitate sizes and distributions were as expected, based on comparisons with small samples run at GRC with the desired heat treating procedures. Thus, a combination of laboratory experiments on small IN718 samples, temperatures measured directly from the heater heads during processing, and the microstructural analysis all confirmed that the heat treatment procedures for the heater head should meet the requirements. The witness coupons were also found to accurately reflect the heater head microstructure and thus capable of verifying the heat treatment.

An analytical model was used to predict the internal pressure loss due to helium permeability through the heater head walls over 14 yr of operation at 650 °C. The results were based on analytical predictions of permeability, using diffusion data reported in the literature along with values of solubility derived from

both experimental and computer models. The predicted loss was found to be only 0.23 Pa ( $3.3 \times 10^{-5}$  psia), using a best estimate for helium solubility in nickel.

### Evaluation of Converter Organics

Organic materials are used in limited amounts in the Stirling converter, primarily in the linear alternator for such uses as electrical insulation, structural bonding, and as a surface in close clearance seals where there might be temporary contact of moving parts. Organics issues in the SRG110 project included radiation tolerance, outgassing, and bond strength. The primary emphasis was placed on the epoxy bond used to hold the permanent magnets to the stator of the linear alternator. The bond was made with 3M Scotch-Weld (3M Company) 2216 B/A Gray epoxy. A cure cycle was selected based on GRC cure kinetics testing, as shown in figure 6, and by evaluating lap shear strength at various cure times and temperatures. In collaboration with Infinia, this cure cycle was then incorporated into the standard processing steps used by Infinia for fabricating the linear alternator. Lap shear samples cured with the optimized cure cycle showed an increase in adhesive strength of about 40 percent at the SRG110 operating temperature, compared to using the standard room-temperature cure cycle. Short-term accelerated aging tests of the epoxy were conducted for up to 150 days at temperatures of 150 and 180 °C, with no degradation being observed. Fatigue testing and aging tests were underway when the SRG110 project was redirected. One issue that remained was achieving acceptable bond strength with adequate margin for the magnet-stator laminate assembly at the expected operating temperature. Two higher-temperature epoxies, Master Bond EP33 and Master Bond Supreme 10HT, were also studied as possible alternatives having higher bond strength at the operating temperature.

The organic adhesives and insulators were not tested specifically for radiation tolerance; however, some limited tests were performed on the Xylan (Metal Coatings Corporation) coating. Literature searches were conducted and vendors were contacted to evaluate compatibility with the SRG110 requirements, and expertise was provided by the Jet Propulsion Laboratory (JPL). In all cases, there was evidence that the selected materials could survive the SRG110 requirement of 50 Krad (Si) behind 1.5 mm aluminum. Radiation tolerance for missions such as Europa, which could reach 4 Mrad (Si) behind 2.5 mm aluminum, would require further evaluation, although organic material selections were made during the project with this goal in mind.

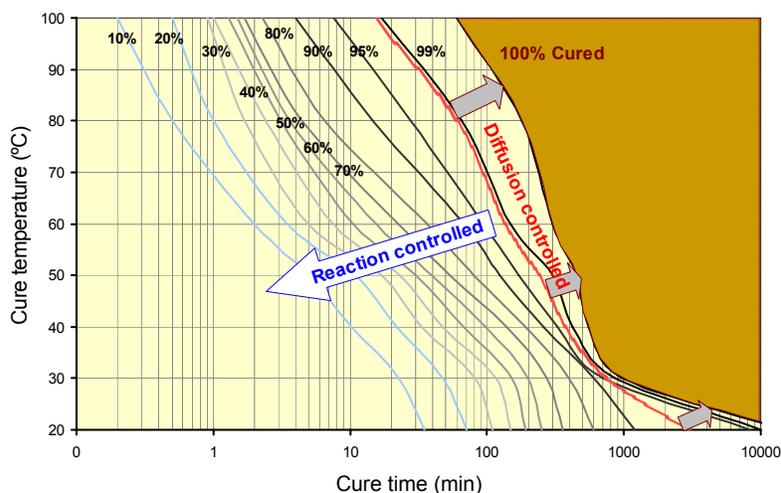


Figure 6.—Time-temperature-transformation diagram showing cure kinetics of 3M Scotch-Weld 2216 b/a gray epoxy.

Outgassing of the organics was a concern since it could indicate decomposition of the organic, and the gas generated could deposit on or react chemically with other components. One of the features of Stirling testing at GRC is the ability to sample the working fluid during operation and analyzed it with an RGA. More than 90,000 hr of operation have been accumulated, with over 23,000 hr on TDCs numbers 13 and 14 and over 9000 hr on TDCs numbers 15 and 16. The Stirling convertors were hermetically sealed for some of these test hours, with the exception of the fill tube. The fill tube was purposely not sealed, so that gas samples could be analyzed. Sampling of the working fluid has shown no evidence of decomposition or outgassing of the organics. A very small amount of carbon monoxide has been observed, which is known to adsorb to stainless steel and desorb during operation. Experience at GRC has indicated great benefits of (1) an initial pump down and bake out of a convertor, (2) followed by operation at a reduced temperature to suppress oxidation, (3) followed by another pump down and bake out, and (4) then, full-temperature operation. Based on the experience with Stirling cryocoolers in flight and terrestrial application and operating experience at GRC, it appears that outgassing or decomposition of the organics in a Stirling convertor will not be an issue for flight.

### Magnets and Linear Alternators

Long life and reliable performance require the magnets of the linear alternator to maintain their properties throughout the mission. Characterization tests were performed on 1-cm cubes of candidate neodymium-iron-boron (NdFeB) magnet materials from various vendors. The remanence, intrinsic coercivity and the magnetization were measured for each of the samples over the temperature range of 20 to 140 °C. The purpose of this test was to verify performance of the magnet material against vendor specifications.

Following characterization, the preferred magnet types were selected for a 200-hr, short-term aging test, with the samples exposed to a field of  $-5.0$  kOe and at 150 °C, conditions far in excess of expected convertor operating conditions and chosen to accelerate any possible aging. Short-term aging tests and initial results are discussed in Niedra (2001). Magnet grades that demonstrated minimal change in properties during the short-term test were then evaluated in a long-term aging test. The long-term test exposed the magnets to a field of  $-6.0$  kOe at 120 °C, conditions somewhat in excess of SRG110 convertor operating conditions to add some test margin. Long-term aging tests of 18,000 hr were completed on two NdFeB magnet grades; additional tests were underway when the project was redirected. The hardware for magnet aging tests is shown in figure 7. Magnets are used in long-life cryocoolers that operate at similar conditions, and thus far, the cryocoolers and the convertors under extended operation test at GRC have not shown signs of degradation. A magnet paddle and testing technique has been developed to characterize the material of a curved magnet as would be used in the alternator, and initial test results indicate that the technique is able to properly characterize the curved magnets.

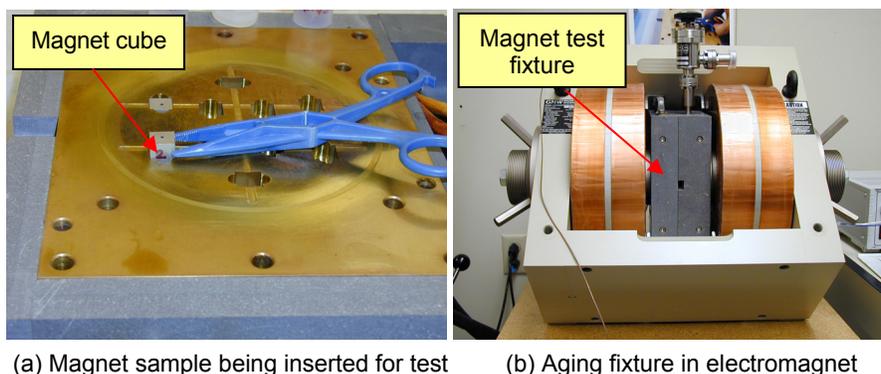


Figure 7.—Magnet aging test capability to support Stirling development at GRC.

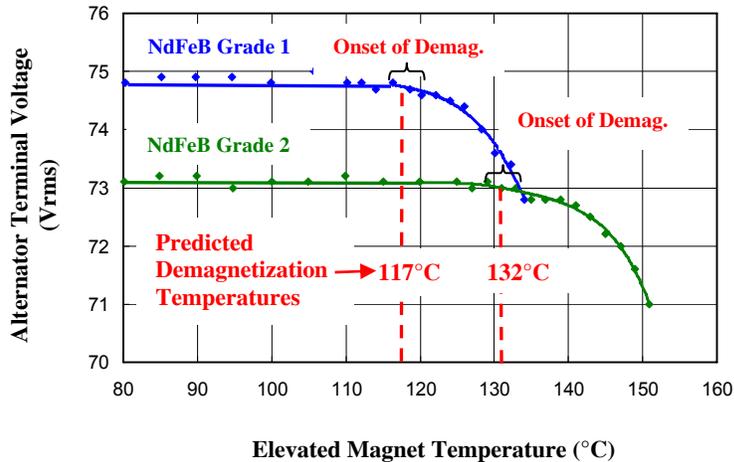


Figure 8.—Comparison of linear alternator demagnetization test results with predictions for two NdFeB magnet grades.

While the magnet characterization tests and aging tests provided data on the strength and demagnetization resistance of the magnet material, a parallel effort developed the capability to predict accurately how the magnets were stressed during operation. Techniques in magnetostatic finite element analysis were developed that predict either two-dimensional or three-dimensional stress states within each magnet. The analysis was validated by demagnetization tests in which the linear alternators were operated at increasing temperatures on an alternator test rig (ATR) until demagnetization was sensed. The analysis and data agreed within the measurement accuracy and variances of the magnet material properties, as shown in figure 8. The overall performance of a TDC linear alternator was also characterized on the ATR. The magnet aging and linear alternator evaluation efforts are discussed by Geng et al. (2001) and Geng, Niedra, and Schwarze (2005).

### Structural Dynamics and Launch Environments

The ability of a Stirling convertor to survive launch loads, while mounted in a generator, was unknown when the 1999 Technology Readiness Assessment prompted the vibration test of TDC number 1. Only the Stirling convertor was vibration tested, since a generator design had not been sufficiently developed. The Stirling convertor was tested up to 12.3 g (0.2 g<sup>2</sup>/Hz) in the GRC Structural Dynamics Laboratory (SDL), in both the lateral and axial directions relative to the convertor piston motion. This was the level specified for input to the generator. This test made no assumptions about amplification or attenuation of the vibration by the generator housing. The results of these initial tests are discussed by Goodnight, Hughes, and McNelis (2000).

Since that time, six additional vibration tests have been performed on relevant Stirling convertors. Two significant design changes were made to the SRG110 generator design, based in part on results from these tests and launch load considerations (Hill et al., 2005). First, the Stirling convertors were connected to one another structurally at the aft end of the pressure vessels to eliminate rotation around the cold flanges that serve as the mounting structure between the Stirling convertors and the generator housing. The two convertors act as a single structure, mounted to the generator housing by the two cold flanges. Figure 9 shows an example of the response of the design prior to this change compared to the response with the connecting tube. The second change was the development of a compliant interface between the spacecraft and the generator.

A simulator of the generator and the spacecraft interface was developed to verify the approach and validate the analytical models. The generator simulator was tested at the GRC SDL in August 2005. Mass

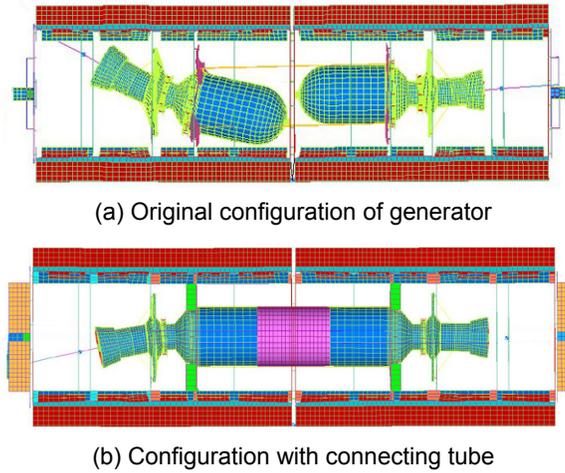


Figure 9.—Comparison of response of Stirling converters with original mounting and improved mounting configurations (displacements exaggerated for clarity).



Figure 10.—TDC mass simulators attached to a common pressure vessel in preparation for vibration test.

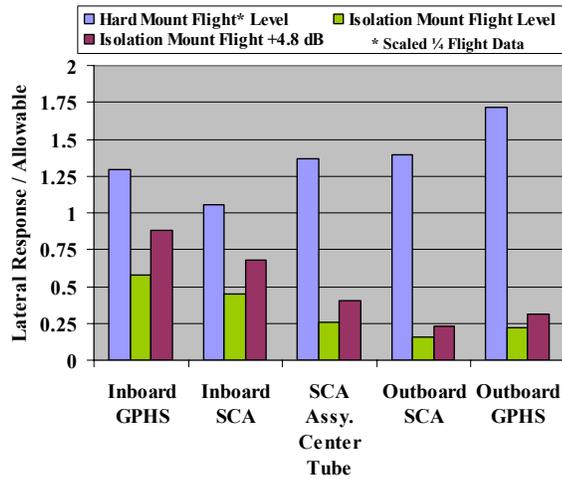


Figure 11.—Lateral response of SRG110 simulator test article in hard-mounted and isolation-mounted configurations; SCA: Stirling convertor assembly.

models of the TDCs were used in this test, mounted inside a cylindrical housing that simulated the SRG110 generator. The TDC mass models were accurate, since they were assembled with actual TDC components. They were connected to one another structurally, as shown in figure 10. The generator simulator was an aluminum tube designed to have dynamic characteristics representative of the SRG110 beryllium housing. Mass models of the GPHS modules were located as they would be in the actual generator, thus providing realistic loading on the generator and the Stirling converters.

Tests were run up to 15.1 g (flight level + 4.8 dB) (peak input 0.3 g<sup>2</sup>/Hz), and the test data confirmed the analytical predictions. The rotation of the Stirling converters was essentially eliminated by connecting the converters in one subassembly, mounted inside the generator. The preload needed on the GPHS modules was maintained throughout the test. This test also demonstrated the feasibility of using a spacecraft interface mount with tuned isolation, as a method to reduce the response of the generator. Response levels were two to nine times lower with this mount than with the hard-mounted configuration, as shown in figure 11. The hard mount flight-level values are scaled from the ¼-flight level test, as tests

could not be run at higher levels in this configuration without exceeding component allowables. The test proved that the generator simulator mounted on the spacecraft interface could withstand vibration up to 15.1 g (0.3 g<sup>2</sup>/Hz). The results for this test are discussed by Lewandowski et al. (2006).

## EMI/EMC

Limited effort has been undertaken on EMI due in part to EMI being an integrated system issue. The tests performed to date have generally been intended to support the SRG110 requirement of MIL-STD-461E, with a modest effort at investigating means to lower the EMI. Three tests have been conducted: (1) 1999 EMI test at GRC that was a part of the Technology Readiness Assessment, (2) 2001 test at GRC to characterize the magnetic field from a TDC, and (3) 2005 test conducted at JPL to investigate electric and magnetic field emissions and methods to reduce the emissions.

In the 1999 test, GRC and JPL measured radiated emissions from TDCs numbers 1 and 2 in the GRC EMI facility (Sargent, 2001). The TDCs were designed with no consideration for EMI, yet it was concluded that the emissions of the TDCs would meet the requirements for the Europa Orbiter and Pluto Kuiper Express missions, but not for the Solar Probe mission (Furlong and Shaltens, 2000).

The 2001 magnetic field characterization test was conducted at GRC to aid in developing an initial strategy for emissions management. The tests used TDCs numbers 5 and 6. Tests were conducted with two controllers, one with harmonic content in the current, and the other with a resistive load resulting in very little harmonic content. The emissions did not vary greatly between the two controllers. The AC magnetic field emission was found to be below that allowed by MIL-STD-461E.

The 2005 test conducted at JPL with TDC number 7 measured the magnetic and electric DC and low-frequency emissions. The low-frequency, electric field tests showed that the emissions were below the levels set by most flight instruments and were primarily due to unshielded cables. The low-frequency, magnetic field emissions were dominated by the 80 Hz operating frequency; 0.5 mm of mumetal shielding reduced the emissions at 1 m by about 20 dBpT. The DC magnetic field was reduced to less than 10 nT, at 1 m with shielding. The conclusion was that the emissions appeared to be able to be reduced to acceptable levels with proper shielding.

## Reliability

The most fundamental requirement for a space power system is reliability. Since it is difficult to prove life of a device that has no wear-out mechanisms, the reliability effort was multi-faceted. It included classic methods such as failure modes, effects, and criticality analysis (FMECA); reliability block diagrams; and fault tree analysis. Probabilistic techniques were applied to many of the critical components. Extended operation tests were conducted to investigate life and reliability. Also, the experience that has been accumulated by cryocoolers in both terrestrial and space applications was studied to find relevant information. The GRC reliability efforts were complementary to and coordinated with the overall LM reliability effort.

A FMECA of the TDC was constructed, and no items were found to be fundamentally lacking in development for the long-life application. Most of the items were addressed by updates to process and inspection procedures, ultimately improving the quality control. This is similar to the experience for the long-life cryocoolers.

Probabilistic analysis was used at GRC on many of the components, with the first being the heater head since it is known that this component will creep and therefore age. This analysis is described in detail under the section on Heater Head Life Assessment. Probabilistic analysis was then performed on other components, including the flexures, magnets, fasteners, and regenerator (Shah et al., 2005a; 2005b). In each case, a model of the component was created, and the influences of all key parameters that could affect proper operation of the component were studied. The parameters that may have a random variation include material properties, physical dimensions, and operating conditions. These analyses utilized, in part, the test results and understanding gained in the various project tasks; in essence, most all GRC tasks

were aimed at improving reliability. No cases were found in which the life requirement of greater than 14 years was unable to be met with high reliability. An effort was also begun at GRC to combine the individual probabilistic reliability analyses into a single probabilistic reliability projection for the complete Stirling convertor. This can be complex as there can be significant interaction among the components and subassemblies. Determination of the method to obtain this convertor probabilistic reliability projection is being continued as part of the ASRG effort.

## Summary

From 1999 to 2006, the NASA Glenn Research Center (GRC) supported the development of a high-efficiency, nominal 110-We Stirling Radioisotope Generator (SRG110) for potential use on NASA missions, including deep space missions, Mars rovers, and lunar applications. Project highlights over this period were described in this report and include: (1) over 23,000 hr of extended-duration, in-air testing of two Stirling convertors in a dual-opposed configuration, including working fluid sampling throughout the testing; (2) over 10,000 hr of extended-duration testing of two Stirling convertors in a thermal vacuum environment; (3) heater head life assessment, including probabilistic analysis, which showed a life of 24.9 yr with 99.9 percent probability of survival ; (4) 18,000-hr magnet aging characterization on typical neodymium-iron-boron permanent magnets; (5) linear alternator demagnetization analysis and verification testing; (6) structural dynamics testing of a single convertor to 12.3 g in both lateral and axial directions to evaluate robustness for the launch environment; (7) structural dynamics testing of a simulated generator to 15.1 g and 0.3 g<sup>2</sup>/Hz maximum; (8) physics-based reliability evaluations of various convertor components; and (9) development and verification of a system dynamic model that includes Stirling engine thermodynamics, linear alternator, convertor mounting, controller, and load.

Key findings include: (1) no degradation in performance in extended operation of hermetically-sealed convertors, (2) no convertor issues found for operation in a thermal vacuum environment, (3) generator should be capable of withstanding launch vibrations up to 15.1 g and 0.3 g<sup>2</sup>/Hz, (4) EMI/EMC levels should be sufficient for most science missions with some mass penalty for shields, (5) reliability studies and supporting technical efforts showed no cases for which the life requirement of greater than 14 yr could not be met with high reliability, and (6) no fundamental barriers found that would preclude use of the Stirling convertor for long life, radioisotope space power applications. Related efforts are now continuing in many of these areas to support the development of the Advanced Stirling Radioisotope Generator with significantly higher specific power.

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