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Abstract

Free-piston Stirling power conversion has been considered a candidate for radioisotope power systems for space for more than a decade. Prior to the free-piston Stirling architecture, systems were designed with kinematic Stirling engines that used linkages and rotary alternators to convert heat to electricity. These systems were able to achieve long life by lightly loading the linkages; however, the live was nonetheless limited. When the free-piston configuration was initially proposed, it was thought to be attractive due to the relatively high conversion efficiency, acceptable mass, and the potential for long life and high reliability based on wear-free operation. These features have consistently been recognized by teams that have studied technology options for radioisotope space power systems. Since free-piston Stirling power conversion was first considered for space power applications, there have been major advances in three general areas of development: hardware that has demonstrated long-life and reliability, the success achieved by Stirling cryocoolers in space, and the overall developmental maturity of the technology for both space and terrestrial applications. Based on these advances, free-piston Stirling convertors are currently being developed for space power, and for a number of terrestrial applications. They commonly operate with the power, efficiency, life, and reliability as intended, and much of the development now centers on system integration. This paper will summarize the accomplishments of free-piston Stirling power conversion technology over the past decade, review the status of development with regard to space power, and discuss the challenges that remain.

1. Introduction

Stirling power conversion technology has progressed through several distinct phases of development. Two key features made the early Stirling engines attractive in the decades that followed. They provided greater efficiency than the steam engines that were in common use, and they proved to be safer to operate than steam engines. It was not uncommon for a steam engine boiler to fail and injure bystanders. The early Stirling engines were closed cycle, and operated with air as the working fluid at atmospheric pressure, which resulted in relatively large cylinders compared to steam engines. They enjoyed commercial success and were commonly produced in the range of 0.2 to 4 kW, with one four-cylinder engine being built in 1853 that produced about 220 kW for use in New York harbour (ref. 1). Safe and reliable boilers were ultimately developed leading to the commercial dominance of steam engines and the demise of atmospheric Stirling engines by the early 1900s.

This status did not change until the 1930s when pioneering research began at Philips Laboratories of Einhoven, Netherlands. The contributions were in several areas with great impact on performance, the first of which was operating the cycle at elevated mean pressure. Either the engine could be charged to the desired elevated operating pressure, or it could be built with a compressor that would pump up the pressure of the engine as it operated. This required the crankcase to operate at elevated pressure, or the working space to be sealed from the crankcase by a seal that could maintain the pressure differential. The second major contribution by Philips was the use of gasses other than air as the working fluid, which originated in their development of cryocoolers. Significant increases in power and efficiency were found in engines with helium or hydrogen as the working fluid, however, both gasses presented challenges in containment with hydrogen proving to be more difficult than helium since it could permeate more easily

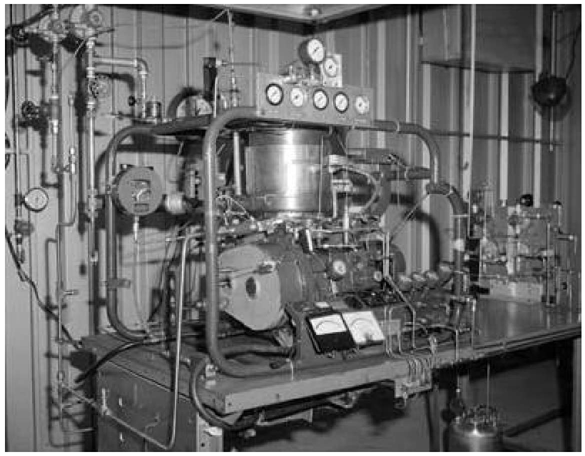

Figure 1.—GPU-3 Under test at NASA GRC.

through polymer o-rings and in some cases, through high-temperature heater tubes. The third contribution was advancing the regenerator in analytical, testing, and fabrication techniques.

Philips envisioned the portable generator as one of the potential applications of their engine. One of the most highly developed single cylinder generators was the GPU-3, developed by General Motors (GM) for the U.S. Army as a fully integrated, 3 kW portable generator. A stripped-down, rhombic drive GPU-3 is shown in figure 1 being tested at the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) (ref. 2). The work at Philips continued into the 1980s resulting in highly developed kinematic engines.

GM actively worked on developing Stirling technology from 1958 through 1970 (ref. 3). Their interest dated back to 1947 after reviewing papers published by Philips. They believed that there were marine applications for the technology, particularly for propulsion systems for submarines. Initially, Philips did not believe that their technology was ready for the applications targeted by GM, therefore, a licensing agreement was not signed until 1958. GM actively pursued applications such as marine propulsion, locomotive power and generator sets, as well as military and space power applications. At that time, they found little interest for automotive applications even though the data showed over 30 percent brake thermal efficiency, and mass that approached that of the Diesel engine. GM focused its' efforts on seals, cost reduction, analytical modeling, and combustors, and received encouragement from the U.S. Army to develop a Stirling outboard motor and small generator sets that would be nearly silent. The licensing agreement with Philips lasted through 1968, however, without having achieved commercial success, development of Stirling technology at GM was terminated by 1970.

Efforts to develop automotive engines continued at low levels, motivated by the multi-fuel capability, quiet operation, low emissions, and increased efficiency. Interest in the automotive Stirling engine increased sharply in the 1970s, motivated in the U.S. by the energy crisis. An automotive Stirling engine project was funded by the Department of Energy (DOE), managed by NASA, with prime contractor Mechanical Technology Incorporated (MTI) of Latham, New York. Initially, Ford Motor Company worked on a parallel effort, partnered with Philips on an engine designated the 4-215 that produced 127 kW that used a swashplate drive mechanism. After about 1 year, Ford made a corporate decision to discontinue their involvement in Stirling to focus their resources on other engine technologies. MTI partnered with United Stirling of Sweden, and developed engines evolving from the four cylinder, dual crankshaft P-40 design. By the mid-1980s, several generations of engines had been developed resulting in the single-crankshaft, V-4, Mod II automotive engine (ref. 4). Increasing power, reducing manufacturing cost, reduce start-up time, and improve throttle response had all been achieved. Engine efficiency was over 38 percent, and a manufacturing study concluded that production cost would be less than a comparable Diesel engine. Engines from before the development were integrated into vehicles and logged over 25,000 km. Mod I automotive engines were integrated into three demonstration vehicles for use by the U.S. Air Force and the U.S. Postal Service. The results of the field trials were positive, with the Air Force van logging more than 14,000 km on JP-4 fuel, Diesel fuel, and unleaded gasoline, and the pick up truck logging over 32,000 km. The postal vehicle was used in daily service for a 3-month trial. Other technologies advanced and the price of fuel stabilized, ultimately leading to the end of the U.S. automotive project. Derivatives of the Philips technology continued to be developed for applications such as stationary power cogeneration, waste heat utilization, and biomass systems. The United Stirling technology has also continued to be developed with one application being in submarines. Although there is some ongoing development of kinematic engines, the great advances mentioned thus far can be viewed as the second general phase of Stirling development; maturation of the kinematic engine.

Invention of the free-piston Stirling by in the 1960s can be viewed as the beginning of the third phase of Stirling development. Development of early free-piston Stirlings focused more on mechanical configuration, dynamics, reliability, and performance, and paid less attention to the conversion of linear motion a useful form of power output or system integration. The potential of free-piston Stirling for a range of applications was recognized by the 1970s resulting in the early research for applications such as terrestrial generators, heat pumps, or space power conversion. As the technology was in its' infancy, much of the effort was consumed in trying to get the hardware to operate reliably, with the intended performance. Power levels were less than 5 kW.

By the 1980s, free-piston Stirling technology had evolved to the point where the intended performance of a new engine design could be achieved after modest development. Integration had improved and the designs were becoming more compact and more efficient. The integrated free-piston Stirling engine with a linear alternator to converts heat to electric power became known as a Stirling convertor. NASA had interest in Stirling power conversion since the 1970s, envisioning the technology to someday be developed into a long-life, high-reliability device. One of the motives for being involved in the automotive Stirling engine project was to gain expertise and help advance the technology, although it was generally thought that the kinematic designs were too complex and life-limited for space power systems. The automotive engines, for example, had a design life of about 1,000 to 2,000 hr.

The maturation of free-piston Stirling technology resulted in MTI being commissioned to design the Space Power Demonstrator Engine (SPDE) and the Component Technology Power Convertor (CTPC) for the SP-100 project. The SPDE was intended to demonstrate the feasibility of free-piston Stirling power conversion for a 100-kWe system that would use multiple Stirling convertors, heated by a nuclear reactor. The SPDE produced 25-kWe with conversion of heat to electricity at about 20 percent efficiency when operated at a temperature ratio of 2.0 (ref. 5). It was a symmetrical design, resulting in dynamically balanced operation. It used hydrostatic gas bearings for non-contacting operation, eliminating all wear mechanisms to enable long life, limited only by the creep of the heater head. The SPDE operated with the hot-end temperature limited to 630 K (357 °C), however, the CTPC was built with capability to operate at temperatures more representative of a nuclear system with the hot end at 1050 K (777 °C) with the cold end at 525 K (252 °C) with design life of 60,000 hr. As a sign of the maturity of the technology, the CTPC generally operated as intended without the need for a developmental effort. When the high-power Stirling development ended in the early 1990s, the CTPC had operated slightly more than 1,500 hr.

2. Stirling for Radioisotope Power

Nuclear and solar thermal power systems in space are generally considered to be in the range of multiple kW's, and radioisotope power systems are commonly considered to be at power levels of <1 kWe. Long life and high reliability are the most fundamental requirements for space power, which presents a developmental challenge for dynamic power conversion in space. One effort by General Electric and Philips in the 1970s under contract to the DOE did consider a highly developed kinematic engine for radioisotope space power (ref. 6). The Stirling Isotope Power System was designed to deliver about 1 kWe with system efficiency of approximately 28 percent. Operation was to be unattended for 6 months; with routine maintenance, the total useful life would be 10 years, with one major overhaul. The engine used a rhombic drive and two rotary alternators, and there were numerous joints in the pressure boundary that consisted of 12 heater tubes, 6 regenerators, and 117 cooler tubes, making the requirement of long life and high reliability difficult. The project resulted in hardware being tested on earth. Free-piston Stirling provides an option with the potential for long life, high reliability, high efficiency, and reasonable mass. The key features are the elimination of all wear mechanisms, elimination of seals, valves and the lubrication system, and the ability to have a dynamically balanced system. Studies were performed as early as 1989 at NASA Glenn to determine the feasibility of free-piston Stirling for a radioisotope power system (ref. 7). Two systems were studied that used either 4 or 8 General Purpose Heat Source (GPHS) modules with electric power output of 240 and 480 W, respectively. Specific power was projected to be 7.1 to 8.0 W/kg. This was an initial study, lacking some of the details needed in flight development; however, it did indicate that a free-piston Stirling radioisotope generator was feasible. The designs were refined by subsequent studies that evaluated a range of applications, (refs. 8 to 11) and generators were proposed over a power range of 200 to 600 W power output with specific power ranging from 5.4 to 8.7 W/kg. As shown in figure 2, the layout placed the GPHS modules around the perimeter of the Stirling heater heads, and each convertor had two pistons and two alternators such that each Stirling convertor would be nearly vibration free. By the early 1990s the potential of free-piston Stirling for radioisotope space power had been recognized, however, some development remained, namely, development at the power levels of interest, system integration, and the need to demonstrate the life and reliability through conclusive data.

An early effort to address the Stirling convertor design came from a 1993 NASA Small Business Innovative Research (SBIR) contract with the Stirling Technology Company (currently known as Infinia Corporation) of Kennewick, Washington. The contract resulted in the design of a free-piston Stirling convertor projected to have 28 percent conversion efficiency with 280 W power output. The system envisioned for this design had redundancy by operating multiple Stirling convertors, each one operating at de-rated power, and in the event of failure of one Stirling convertor the remaining convertors would increasing their operating points to maintain system power. Generator mass was projected to be 36.2 kg, resulting in specific power of 7.7 W/kg. At the conclusion of the contract, no hardware had been built or tested.

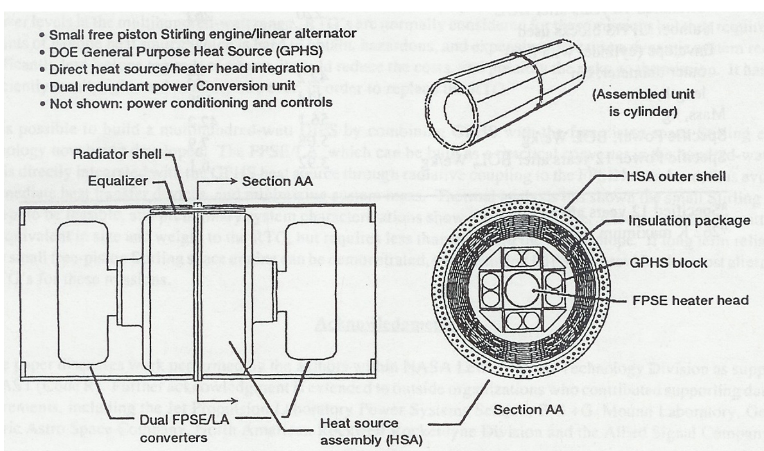

Figure 2.—Generator configuration from 1991 GRC study, with two free-piston Stirling convertors, each one with two pistons and two alternators.

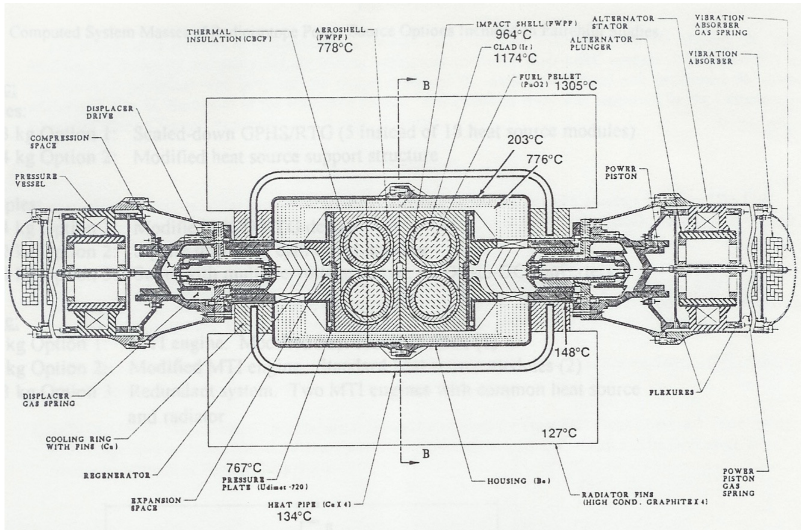

Figure 3.—Stirling generator from 1994 Fairchild study, with two free-piston Stirling convertors, each one with a dynamic balancer, sharing four radiator panels.

DOE also commissioned a study of radioisotope free-piston Stirling for space application in 1994 by Fairchild Space and Defense Corporation (ref. 12). The study made use of a 75-W Stirling convertor generated by MTI under contract to GRC. Three system options were proposed for a Pluto Fast Flyby (PFF) mission. The PFF mission called for a power system of about 10 kg mass, and 69 W power output at the end of a 9.2-year mission. The Stirling power system masses ranged between 7.3 kg for a non-redundant system, to 11.3 kg for a redundant system. The 75-W Stirling convertors were projected to be 3.75 kg in mass (20 W/kg) including a dynamic balancer, and 23 percent efficient. A cross section of the generator is shown in figure 3.

These studies indicated that a free-piston Stirling radioisotope generator could offer desirable performance; however, a Stirling convertor with the necessary features had not been developed. The state-of-the-art in relevant free-piston Stirling designs showed operation of 1,500 hr on the CTPC at the 12-kWe level, and 1,100 hr on a 3-kWe Engineering Model (ref. 13) both efforts under contract to NASA. The EM was tested in 1983 and had hydrostatic gas bearings on both the piston and the displacer.

By the mid-1990s, conceptual designs of Stirling radioisotope generators had been proposed; however, there were no convertors under test, and there were no efforts being funded by the government to develop the necessary technologies other than small contracts for similar applications and from SBIR contracts. One example was the "Innovative Integration of Long-Life High Efficiency Thermal Convertors Using Proven Free-Piston Stirling Machines" contract reported in 1999. The project's final report showed that two thermodynamically isolated convertors, connected in parallel to one controller after the tuning capacitors, would synchronize the pistons and was a robust and stable configuration (ref. 14). The SPDE had demonstrated dynamically balanced operation; however, with a common working space, the loss of the working fluid would result in both power pistons stopping. With multiple convertors synchronized through the electric controller, loss of working fluid in one convertor would not require the other convertor to stop, which was considered a good feature on a radioisotope power system.

A study was commissioned by DOE in 1997 to evaluate candidate power conversion technologies for a high-efficiency radioisotope power system. The study Alkali Metal Thermal Electric Conversion (AMTEC), Stirling, and thermophotovoltaic (TPV) (ref. 15). The report concluded that Stirling was an available technology, and that AMTEC offered some attractive features, leading to the Advanced Radioisotope Power System project with Lockheed Martin (LM) of Valley Forge, Pennsylvania, as the

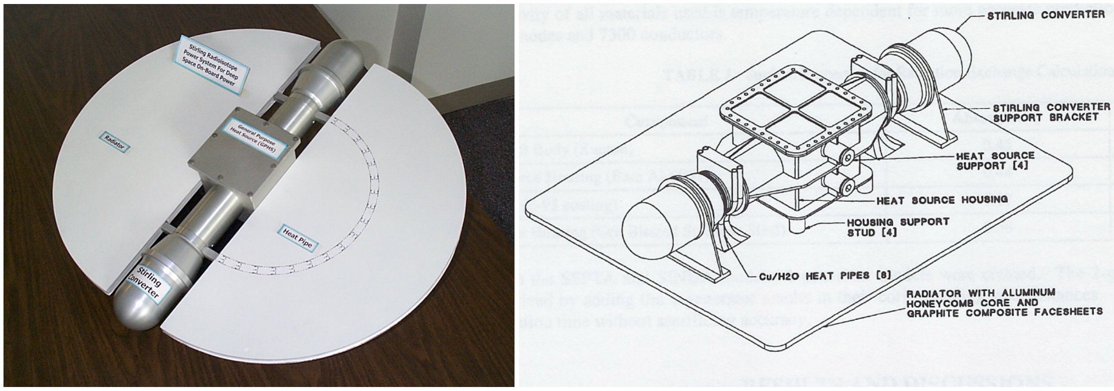

Figure 4.—Orbital Sciences Corporation generator design, with two GPHS modules and two early TDC Stirling convertors. Generator with circular radiator panels on left, and self-supporting design with flat radiator panel on right.

System Integration Contractor (SIC). A low-level effort to develop Stirling technology as a backup was initiated by DOE with technical consultation provided by GRC. The Technology Demonstration Convertor (TDC) was developed by Infinia Corporation to convert heat from one GPHS module to electric power, and by 1999 had demonstrated efficiency greater than 20 percent from heat input to AC electric power output. The TDC had a mass of about 6 kg with mass reduction expected during flight development. In support of DOE, Orbital Sciences Corporation (OSC) investigated several generator designs to assess feasibility of the integrated system (refs. 16 and 17). A model of one concept is shown in figure 4, which includes two GPHS modules and two TDC’s in dual-opposed configuration. Figure 4 also shows the self-supporting concept by OSC that was projected to achieve specific power of approximately 8 W/kg (ref. 18).

The status of free-piston Stirling for space power had changed measurably by 1999 since some of the key features had now been demonstrated. A 10-W convertor based on non-contacting operation had operated for over 50,000 hr at Infinia with no measurable change in performance, and multiple convertor operation with vibration control had been addressed by GRC through SBIR’s with Infinia. The TDC was designed to operate with heat from one GPHS module and achieved the nominal goals established for power and efficiency, but was somewhat over the goal for mass. Under contract to DOE, Infinia demonstrated TDC power of over 55 W, and efficiency of over 27 percent with non-contacting operation through the use of flexures. Due to the efforts of the U.S. Air Force Research Laboratory, flight worthy Stirling crycoolers had been developed and about 9 were being used in space. Little was known about radiation tolerance, electromagnetic interference and electromagnetic, compatibility (EMI/EMC), flight controller design, and survivability of launch vibration.

Development of the AMTEC generator was discontinued in 1999 and a joint DOE/NASA/industry team was commissioned to assess the readiness of Stirling power conversion for flight development. The study team included DOE-Germantown, NASA GRC, the Jet Propulsion Laboratory (JPL), OSC, LM-Valley Forge, and LM-Denver. The key issues that needed to be evaluated to determine the readiness were 1) launch load capability, 2) EMI/EMC, and 3) performance mapping, evaluation of 4) radiation tolerance, 5) controller design, 6) a failure modes effect and criticality analysis (FMECA) of the Stirling convertor, and 7) a fault tolerant system configuration. The tasks were divided among the team members (ref. 19) and TDC’s nos. 1 and 2 were used for launch vibration testing and EMI testing at GRC (ref. 20) with performance mapping being performed at Infinia. Radiation survivability was evaluated by GRC with support from JPL, and a controller design was developed by LM-Denver. A FMECA was prepared by GRC with support from Infinia, and two system concepts were proposed that fulfilled the requirement for a fault tolerant system. Based on relevant information from flight cryocoolers and the long life that had been demonstrated by operation of the 10 W convertor at Infinia, it was determined that the TDC was capable of being developed for flight.

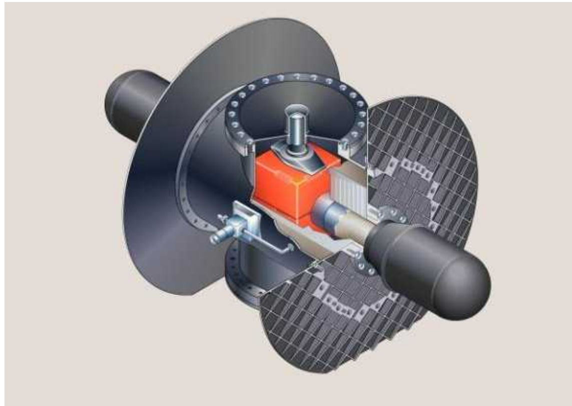

Figure 5.—Radioisotope generator proposed in the 1999 Technology Readiness Assessment by Lockheed Martin.

Due to the focused effort of 1999, the status of the technology had changed by early 2000. Some of the key issues were addressed by gathering existing information. Integrated systems were proposed as shown in figure 5, which considered more details than had appeared in previous studies (ref. 21). The power output was projected to be 112 W at BOM and the mass was projected to be 26.6 kg for a specific power of 4.2 W/kg. For some of the other key issues, tests had been completed that provided data including response to launch dynamics, EMI, and performance mapping. The launch vibration test culminated in 3-min long, axial and longitudinal tests at 12.3 g (0.2 g2/Hz) with the TDC operating at full power. The TDC survived the vibration test at qualification test level used for input into a generator, and then operated for more than 40 hr afterward, before being disassembled for inspection, which showed no signs of wear or damage.

3. The 110 W Stirling Radioisotope Generator

Based on the findings of the Technology Readiness Assessment, development of a 100-W class Stirling radioisotope generator (SRG110) was authorized. Contracts were let for the conceptual design of a generator based on a generic set of specifications for a deep space mission. The specifications called for the generator to maximize specific power, with a life requirement suitable for deep space missions. The designs were initially use in deep space; however, a modification was later issued to include operation on the surface of Mars. LM was selected as the SIC and development of the SRG110 began in May 2002. The LM design enclosed two GPHS modules and two Stirling convertors inside a beryllium structure that acted as structure and radiator (ref. 22). By placing the Stirling convertors with their heater heads apart, the generator could tolerate shutdown of one Stirling convertor without needing the other convertor to be shut down. Shutdown of the second convertor would depend solely on the vibration that the end user could tolerate. The generator was projected to produce 114 W at 27 kg mass, for a specific power of 4.2 W/kg. Development continued with LM refining the design of the generator and Infinia refining the Stirling convertors.

Prior to selection of the SIC, a technology effort was started at GRC to address many of the key aspects of the Stirling convertor and its integration into a generator. Since the technology effort was to support flight development, all of the tasks ultimately contributed to life and reliability. The GRC effort focused on materials, both metallics and organics, structures, life analysis and testing, Stirling convertor and controller tests, magnets and linear alternators, launch environments, EMI, and reliability (ref. 23). The generator design matured as did the TDC based on considerations of system integration and flight hardware production. The SRG110 became the most comprehensive design of a Stirling radioisotope generator. In final design resulted in projected 116-W power output based on 496 W of heat input from

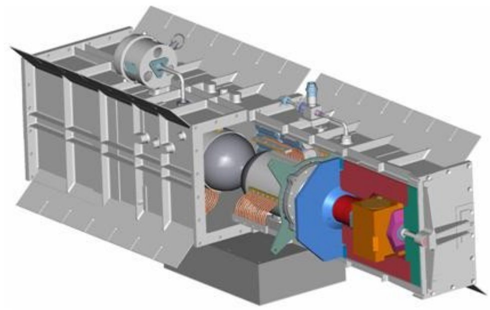

Figure 6.—SRG110 generator with dual-opposed Stirling convertors located with hot ends away from one another.

the two GPHS modules, and 101-W power output after 14 years in space, with mass of 32.5 kg for a specific mass of 3.6 W/kg. figure 6 shows an image of the final design of the SRG110 generator.

The SRG110 flight development caused the status of free-piston Stirling power conversion to change significantly by 2005 with contributions from LM, Infinia and GRC. These advances were generally in the areas of life, reliability, and system integration. Whereas Stirling efforts of the 1970s and 1980s were often consumed with steady, repeatable operation and achieving predicted levels of performance, the major efforts in SRG110 dealt with system integration. Some of the more significant advances will be briefly described.

3.1 Materials

The heater head is a critical component in achieving long life of the convertor and is the only component that is known to change with time in a convertor that has had all wear mechanisms eliminated by design. 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 analyses, material testing, and by using an existing database with creep data up to 87,000 hr (9.9 years). Initial tests were used to optimize the grain size, since larger grains that normally provide low creep rates resulted in too few grains through the thin walls. 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 10, 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 has been defined as the onset of tertiary creep, which occurs at about 70 percent of time to creep rupture for this material. The calculations showed a heater head life of 188,000 hr (21.5 years) for a PoS of 99.9 percent, and 116,000 hr (13.2 years) for a PoS of 99.99 percent (ref. 24).

The analysis was compared by 1-, 3-, and 6-month accelerated tests of heater head pressure vessels, with increased pressure used to accelerate creep. All tests were run at 650 °C in the critical area at the hot end of the regenerator knowing that life can be extended by reducing the temperature. Through the project, lifing analysis was refined for the only component that can limit the life by aging. With a modest amount of uncertainty in the projections, the technique can be applied to heater heads made from other heats of IN718, or potentially scaled to project life with other similar nickel base superalloy materials.

The regenerator is a matrix of random metal fibers sintered together that have posed a concern with respect to reliability if some fibers became 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 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 by measuring the amount 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 the optimized process followed by a controlled cleaning process.

Organic materials are used in limited amounts in the Stirling convertor, 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 were a concern in the SRG110 project for 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 (General Electric Co.) 2216 B/A Gray epoxy. A cure cycle was developed based on the cure kinetics, and by evaluating lap shear strength at various cure times and temperatures. 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 the cure cycle recommended by the manufacturer. Short-term accelerated aging tests of the epoxy were conducted for up to 150 days with no degradation being observed.

The organic adhesives and insulators were not tested specifically for radiation tolerance; however, some limited tests were performed on the Xylan (Whitford) coating. Literature searches were conducted and vendors were contacted to evaluate compatibility with the SRG110 requirements, and expertise was provided from 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 a mission kit.

Outgassing of the organics was a concern since it could indicate decomposition of the organic, and the gas generated could deposit 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. A system was developed by which a small amount of the working fluid could be sampled and analyzed by a Residual Gas Analyzer (RGA). The manifold uses welded connections and the Stirling convertors were hermetically sealed during some of the tests, with the exception of the fill tube. The fill tube was purposely not sealed, so that gas samples could be analyzed. More than 90,000 hr of operation have been accumulated with over 23,000 hr on TDC's nos. 13 and 14, and over 9,000 hr on TDC's nos. 15 and 16. 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 an initial pump-down and bake out of a convertor, followed by operation at temperature reduced to suppress oxidation, followed by another pump down and bake out. 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.

3.2 Magnets and Linear Alternators

Long life and reliable performance requires the magnets of the linear alternator to maintain their properties throughout the mission. Characterization tests were performed on 1-cm cubes of candidate magnet material 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. The hardware for magnet aging tests is shown in figure 7. This selected demagnetization field and temperature were far in excess of what was expected in the SRG110. 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. This field and temperature were once again in excess of the SRG110 operating

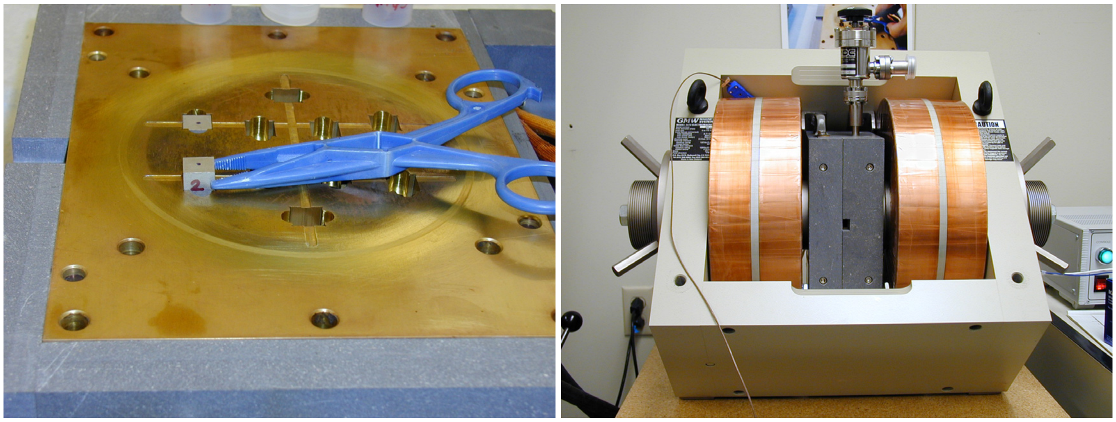

Figure 7.—Magnet test at GRC, with a magnet sample being placed in the aging fixture on left, and the magnet aging fixture installed in electromagnet on right.

conditions; however, they were not as severe as in the short-term test. The long-term magnet test lasted for 18,000 hr (ref. 25). 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 appear to indicate that the technique is able to properly characterize the curved magnets.

While the magnet characterization tests and aging tests provided data on the strength 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 until demagnetization was sensed. The analysis and data agreed within the measurement accuracy and variances of the magnet material properties.

3.3 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 assessment prompted the vibration test of TDC no. 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 g2/Hz), which 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.

Since that time, 6 additional vibration tests have been performed on relevant Stirling convertors. The SRG110 generator design evolved, based in part on results from these tests and launch load considerations (ref. 26). Two significant design changes were made. 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.

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 Structural Dynamics Laboratory in August 2005. Mass models of the TDC’s were used in this test, mounted inside a cylindrical housing that simulated 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 8. The generator simulator was an aluminum tube designed to have dynamic characteristics

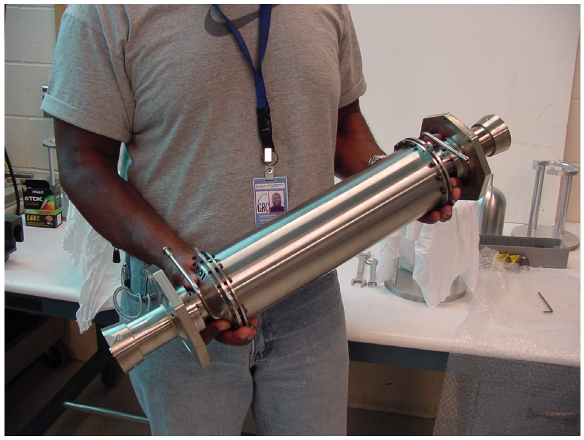

Figure 8.—TDC mass simulators attached to a common pressure vessel in preparation for vibration test.

representative of the SRG110 beryllium housing. Mass models of GPHS modules were located as they would be in the actual generator, thus providing realistic loading on the generator and the Stirling convertors.

Tests were run up to 15.1 g (0.3 g2/Hz), and data confirmed the analytical predictions. The rotation of the Stirling convertors was essentially eliminated by connecting the convertors in one subassembly, mounted inside the generator. The preload needed on the GPHS modules located between the ends of the generator housing and the heater heads was maintained throughout the test. This test demonstrated the feasibility of using a spacecraft interface mount with tuned isolation as a method to reduce the response of the generator. Response with the spacecraft interface mount was up to 9 times lower than with the hard-mounted configuration, and that the generator simulator mounted on the spacecraft interface could withstand vibration up to 15.1 g (0.3 g2/Hz). Prior to 1999, survival of the Stirling convertor to launch loads was unknown, and by 2005, the capability to survive launch loads up to 0.2 g2/Hz had been demonstrated, with analysis indicating the capability to survive up to 0.3 g2/Hz.

3.4 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-Spec 461E, with a modest effort at investigating means to lower the EMI. Three tests have been conducted to date, including the 1999 EMI test at GRC that was a part of the Technology Readiness Assessment, a 2001 test at GRC to characterize the magnetic field from a TDC, and the 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 TDC nos. 1 and 2 in the GRC facility (ref. 20). The TDC's had been designed with no consideration for EMI, yet it was concluded that the emissions of the TDC's would meet the requirements for Europa Orbiter and Pluto Kuiper Express, but not for the Solar Probe mission (ref. 19).

The 2001 magnetic field characterization test was conducted at GRC to aid in developing an initial strategy for emissions management. The tests used TDC's nos. 5 and 6. Tests were conducted with two controllers, one with in 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 no. 7 was intended to measure the magnetic and electric DC and low-frequency emissions. It was found that electric field emissions were compatible with most flight instruments. The low-frequency electric field tests showed emissions due primarily to unshielded cables, and that the emissions were below the levels set by most flight instruments. Low-frequency magnetic field emissions were found to be dominated by the 80 Hz operating frequency, and that 0.5 mm of mumetal shielding reduced the emissions at 1 m by about 20 dBpT. The DC magnetic field was found to be able to be reduced to <10 nT at 1 m with shielding. The conclusion was that emissions appeared to be able to be reduced to acceptable levels with proper shielding.

Prior to 1999, there was no information available relative to meeting EMI/EMC requirements for spacecraft. This issue will remain open until a complete flight generator has been tested. Data from the three tests indicate that low levels can be achieved that are sufficient for most science missions; however, there will be some mass penalty if shielding is needed.

3.5 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 is multi-faceted. It includes classic methods such as FMECA, reliability block diagrams and fault tree analysis. Probabilistic techniques have been applied to many of the critical components. Extended operation tests have been conducted to investigate life and reliability. Also, the experience that has been accumulated by cryocoolers in both terrestrial and space application has been studied to find relevant information.

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 of the long-life cryocoolers.

Probabilistic analysis was used at GRC on many of the components, with the first component being heater head since it is known that this component will creep and therefore age. Probabilistic analysis took into account variability in the material property, manufacturing dimensions, operating pressure, and temperature. Analysis of the heater head indicated a POS of 99.99 percent for a 13-year life with the life being most sensitive to the uncertainties in the material properties. It should be noted that this life was calculated with the heater head at the full design temperature at all times, which is an unlikely scenario, and that the definition of end-of-life used in the analysis was the onset of tertiary creep, which is about 70 percent of the time to creep rupture. Probabilistic analysis was then performed on other components, and no cases were found in which the life requirement of >14 years was unable to be met with high reliability.

Extended operation was intended to provide data on operation over time. The test stands were designed with the capability to try to find changes in operation over time, even if the overall performance of the convertor had not changed (ref. 27). One example is the use of an RGA to monitor the working fluid. Six convertors have undergone extended operation at GRC (ref. 28). TDC's nos. 13 and 14 have accumulated over 23,000 hr of operation, TDC's nos. 15 and 16 have accumulated over 9,000 hr, and TDC's nos. 5 and 6 recently completed a 10,000 hr test. During operation, changes in any measurable parameter will try to be sensed. There has been no indication of any changes based on the gas analysis (ref. 28). Small amounts of contaminants have been detected, however, they have either come from outside atmosphere permeating into the working fluid, or from known internal sources, such as trapped pockets. After a total of over 90,000 hr of operation, there has been no indication if any outgassing or decomposition of the organics. More than 2.6×1010 cycles have been accumulated during these tests with no failures other than facility support equipment. The extended operation tests at GRC are not accelerated life tests, as there is no known method for accelerating a life test of a complete Stirling convertor. One might accelerate the life of a component, but not a complete convertor.

3.6 Controller Development

In 1999, there were no designs for flight controllers. A flight controller must provide autonomous operation and have high reliability, in addition to meeting mission specific requirements such as temperature and radiation tolerance. Since that time, there have been fully autonomous controllers have been designed, however, none of the designs for space have been built. An advanced controller is presently being developed at GRC that will make use of power electronics to eliminate the tuning capacitors. The controller will be used in a future test that will be conducted in the thermal vacuum facility at GRC, and is intended to operate a pair of Advanced Stirling Convertors (ASC) in the dual-opposed configuration in extended operation. Extended operation with the advanced controller is scheduled to begin in late 2006.

3.7 Advanced Technology

Advances have been made in the pursuit of improved performance. The most common metric used to evaluate generators for space power is the specific power. The TDC that was used in the SRG110 design had specific power of 15 W/kg. Through an advanced technology effort at GRC, many of the technologies necessary for significant increase in specific power were developed (ref. 29). One example of an increase in specific power was shown in the EE-35 developed by Sunpower (ref. 30). The EE-35 was sized for half of the heat from a GPHS module and achieved approximately 90 W/kg. A more recent project has applied this technology to the ASC, sized for the heat from one GPHS module. The ASC has been developed by Sunpower under contract to GRC and has achieved similar levels of specific power. These high levels of specific power were projected to be possible in the past; however, the EE-35 and the ASC are the first convertors to demonstrate this in hardware. With these Stirling convertors, it appears that a generator could achieve approximately 8 W/kg. This level of specific power is important as it could enable a new class of missions known as radioisotope electric propulsion missions (ref. 31).

Higher specific power of the Stirling convertor has not compromised the ruggedness. The most recent designs appear to be able to withstand even higher levels of random vibration than earlier designs. At the onset of the SRG110 project, Stirling convertors had been tested to 12.3 g (0.2 g2/Hz) random vibration. The EE-35 was tested at GRC in 2004 and survived nearly 24 g (0.8 g2/Hz) vibration. The only failures noted were components that would not be in the flight generator. Designs of generators, mounting configurations for attaching the Stirling convertors to the generator, and spacecraft adapters have been developed that should allow a Stirling radioisotope generator to survive launch loads up to 15.1 grms (0.3 g2/Hz) input to the generator (ref. 32).

Another area where advanced technology is providing a benefit is in the controller. Previous free-piston Stirling controllers used tuning capacitors between the linear alternator and the controller to compensate for the inherent inductance of the linear alternator. A relatively new technique to minimize reactive current without the need for tuning capacitors makes use of power electronics. This technique senses the piston position or velocity, and uses a switching technique to force current to flow in the phase desired. Tuning capacitors occupy significant volume, and with requirements for mounting, wiring, shielding, and the mass of the tuning capacitors themselves, resulted in controller mass greater than desired. GRC has studied the various options for configuring APFC controllers (ref. 33), and is developing controllers for use in air and in vacuum. Current APFC controllers being designed and tested at GRC are a part of the mass savings that enable the generator with specific power of 8 W/kg. Controllers of this type have been operated successfully at GRC in addition to a few other organizations, and have been used to synchronize dual convertors to minimize vibration and correct the power factor.

4. Current State of Development

4.1 Current State of Development

Detailed Stirling power convertor designs now exist that are applicable to space power, as demonstrated by the TDC and the ASC. They are detailed designs that are well understood and have been well characterized. Similarly, detailed generator designs now exist that are fully applicable to space power and are not merely conceptual. While mass growth may be expected as a space power generator design matures, the SRG110 design had modest mass growth. It was originally proposed to be about 27 kg mass, and in the most mature form tallied 34 kg with margin, however, it must be realized that the generator had taken on more requirements during detailed design of the Engineering Unit generator. Furthermore, many of the components have been built including the Stirling convertors and the beryllium housing. Mass margin that should need to be carried on this design has been reduced due to the maturity of the development.

Stirling convertors at the power levels needed for radioisotope space power systems have advanced from about 15 W/kg for the TDC, to 90 W/kg for the ASC. These designs have undergone initial testing including performance testing, vibration testing, and EMI testing. While there has not been a complete suite of tests to completely characterize the convertors for flight, the heritage provided by long life cryocoolers containing the same basic technologies provides some assurance the flight development will be successful.

A few examples of long life in free-piston Stirling power conversion have been created. The longest life demonstrated in free-piston Stirling power conversion comes from the Atomic Energy Authority Research Establishment, Harwell, United Kingdom. Designs of the Thermo-mechanical Generators (TMG) were developed in the range of 25 to 65 W output. The key feature of the design that enabled long-life was non-contacting operation, achieved by using diaphragms to support the moving components (ref. 34). Two TMG's were operated for approximately 110,000 hr each, without failure until operation was terminated by choice. The Harwell convertors were not high specific power and would not be applicable to space power. Other sources of data are becoming available with over 90,000 hr of operation on TDC's at GRC, and over 3,000 hr on the EE-35's. Preparations are underway to conduct extended operation testing of ASC's at GRC starting in 2006.

Hermetic sealing of Stirling power convertors has recently been demonstrated. While this should not present a significant challenge, and it is common in Stirling cryocoolers, it remained unproven in power convertors until recently. ASC convertors are being prepared for hermetic sealing by Sunpower under NASA sponsorship.

As evidence of the focus on system integration that Stirling power conversion has encounter, detailed designs of controllers have now been developed. Prior to 1999, all controller designs that existed were generally research controllers in that they did not consider life and reliability in production, and did not consider the need for fully autonomous operation. This challenge has been met, and controllers have been designed with system integration in mind, and controllers are currently being designed and developed that have been influenced by the lessons learned in the first designs.

Extensive work has been performed on materials for long life and high reliability. Methods of characterizing the critical materials, particularly in the hot end of the Stirling cycle, have been developed, as have analytical techniques to predict and ensure long life. It has been found that neither the metallics nor the organics appears to present a problem for long life. With regard to materials, the area that may have enjoyed the greatest advances over time is in joining technology. Independent of the advances in Stirling technology, the materials community has made great strides in a wide range of joining techniques that are applicable to Stirling convertors. These include electrostatic spark deposition, laser welding, diffusion bonding, and stir friction welding.

Prior to 1999, there was no data on launch survivability of free-piston Stirling power convertors. Initial tests showed an acceptable level of robustness, but the upper limits were unknown. Designs have advanced, and tests have been conducted successfully up to very high levels that show the Stirling convertor to be able to survive near the limits of the heat source and up to the highest vibration levels produced by the largest launch vehicles. Tests are scheduled for the ASC's that will investigate this further, and analysis is ongoing on the integration of Stirling convertors into the generator.

A modest effort to address EMI has been conducted; however, it appears that there are no inherent limitations for a Stirling radioisotope generator in meeting a common set of requirements for space. It is clear that a concerted effort will be needed for a Stirling generator to meet the requirements of the more demanding missions such as interplanetary and interstellar probes. This area has purposely been left as the responsibility of the mission that needs particularly demanding levels of EMI. For less demanding applications, the benefit enjoyed by Stirling is that the emissions are tonal, being generally at the operating frequency of the convertor and at the harmonics of the operating frequency. This current knowledge can be contrasted to 1999 when there was no knowledge on the subject. Prior efforts in space power Stirling, such as the SP-100 project did not have active tasks in this area.

Great advances have been made in Stirling analysis in two areas. One area is Stirling cycle analysis through the use of Computation Fluid Dynamics (CFD). This technique has been successfully applied at GRC to create a complete, three-dimensional model of a Stirling convertor (ref. 35). Without the need for calibrating the model against data, the results have tracked test data quite well. Advances in parallel processing, the commercial software, and analytical techniques developed at GRC now allow complete simulations to be run in days, whereas estimates from a few years ago indicated that complete simulations may take as long as one year to converge. CFD analysis has not yet been used to influence a design prior to testing hardware, but the capability has recently been demonstrated and now needs to be exercised.

Another area where analysis has made great strides is in system modeling, particularly in modeling the interactions of the non-linear dynamics of the Stirling convertor with the controller. The capability has been developed to model a Stirling power system from end-to-end, including the heat source, the Stirling engine and alternator, the controller and power management system, the heat sink and the end-user load, including all details of the interactions between the subsystems and the environment (ref. 36). The GRC developed System Dynamic Model (SDM) typically uses a simplified representation of the thermodynamics to speed analysis. In most cases, this is sufficiently accurate to predict transient response and check for system stability. The capability has been developed at GRC to allow SDM to interact with the commercial Sage software to use a more accurate thermodynamic model. SDM is used regularly at GRC to support controller development and high-power system studies.

The greatest area of advancement in free-piston Stirling power convertors over the past decade is in system integration. This is particularly true for radioisotope space power since the inception of the SRG110 project. System integration is being performed for not only space power applications, but also for terrestrial applications, both commercial and military. Stirling power conversion projects of the past typically focused on development of the Stirling power convertor with a notional system into which the Stirling convertor would fit. Even in the SP-100 project for example, system integration was somewhat speculative. Today, Stirling system integration regularly considers the necessary aspects of thermal, structural, structural dynamic, controller, and end-user load integration. In SP-100, there was a concept for the controller and power management system; however, the design was not in sufficient detail to transition to flight application. It is now common to design controllers that have the necessary reliability and operational safeguards for fully autonomous operation. Many of the details that appear to be small, but can have an impact on system mass or performance, have been realized through the SRG110. As development of the Stirling radioisotope generator continues, large unexpected mass growth is less likely to occur than when the effort began in 1999.

With the success of the ASC, the SRG110 project has been redirected by NASA to integrate a pair of ASC's into the SRG110 generator, and the project has been renamed the Advanced Stirling Radioisotope Generator (ASRG) project. The purpose of the ASRG is to demonstrate an integrated generator that makes use of the increased efficiency and reduced mass offered by the ASC's. The generator will be electrically heated to simulate the plutonium heat source and is scheduled to be assembled in late 2007 for subsequent test. Since the generator will be a combination of SRG110 components and ASRG components, the specific power will be less than 8 W/kg, however it will be almost double the specific power of the SRG110.

Summary

Free-piston Stirling power conversion technology for radioisotope space power applications has advanced dramatically in the last 7 years. In 1999, it was in a technology development phase, wherein the effort was focused primarily on achieving improved performance such as power and efficiency, life and reliability, addressing the unknowns such as EMI and surviving launch loads, and seeking repeatable, predictable performance. This was all being performed in an attempt to respond to the characteristics needed by a potential end-user application, where the key requirements are long-life, high reliability, with the necessary mass, power and efficiency. Many of the key features were based on potentials, projections, and analyses, but at that time, had not yet been proven in hardware or with test data. Having achieved all of the necessary metrics in the 1999 Technology Readiness Assessment, free-piston Stirling power conversion technology was able to move into a flight development phase, with the effort being shifted toward mitigating risk and system integration. Many of the characteristics that were previously unproven have been addressed by testing hardware and generating data. Where analysis is used, it is now performed in much greater detail than previously. As of 2006, many of the features of free-piston Stirling for space power have been addressed, with results that have been quantified and proven, with test data now in hand, and with no fundamental barriers found that would preclude its use for long life, radioisotope space power applications. Many of the items that still require some attention stem from the issues associated with system integration. Some of those areas requiring further attention include development and testing of a flight quality controller, demonstration of operation in a fully integrated generator interfacing with a spacecraft-like load, and life and reliability in an integrated, flight-like system. Over the past 7 years, free-piston Stirling power conversion has experienced great progress with regard to system integration, with many noteworthy accomplishments, and has moved into a new phase of development.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT
Free-piston Stirling power conversion has been considered a candidate for radioisotope power systems for space for more than a decade. Prior to the free-piston Stirling architecture, systems were designed with kinematic Stirling engines that used linkages and rotary alternators to convert heat to electricity. These systems were able to achieve long life by lightly loading the linkages; however, the live was nonetheless limited. When the free-piston configuration was initially proposed, it was thought to be attractive due to the relatively high conversion efficiency, acceptable mass, and the potential for long life and high reliability based on wear-free operation. These features have consistently been recognized by teams that have studied technology options for radioisotope space power systems. Since free-piston Stirling power conversion was first considered for space power applications, there have been major advances in three general areas of development: hardware that has demonstrated long-life and reliability, the success achieved by Stirling cryocoolers in space, and the overall developmental maturity of the technology for both space and terrestrial applications. Based on these advances, free-piston Stirling convertors are currently being developed for space power, and for a number of terrestrial applications. They commonly operate with the power, efficiency, life, and reliability as intended, and much of the development now centers on system integration. This paper will summarize the accomplishments of free-piston Stirling power conversion technology over the past decade, review the status of development with regard to space power, and discuss the challenges that remain.

15. SUBJECT TERMS
Stirling engine; Nuclear electric power generation; Deep space; Random vibration; Reliability; Mars

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