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Developmental Considerations on the Free-Piston Stirling Power Convertor for Use in Space

Jeffrey G. Schreiber
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May 2007

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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 with rotary alternators to convert heat to electricity. These systems were proposed with lightly loaded linkages to achieve the necessary life. 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. These features have consistently been recognized by teams that have studied technology options for radioisotope 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: demonstration of life and reliability, the success achieved by Stirling cryocoolers in flight, and the overall developmental maturity of the technology for both flight and terrestrial applications. Based on these advances, free-piston Stirling convertors are currently being developed 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, and discuss the challenges that remain.

Nomenclature

AC	alternating current
AFRL	Air Force Research Laboratory
AMTEC	alkali metal thermal electric conversion
APFC	active power factor correction
ASC	advanced Stirling convertor
BOM	beginning of mission
CFD	computational fluid dynamics
CTPC	component technology power converter
DC	direct current
DOE	Department of Energy
EM	engineering model
EMI/EMC	electromagnetic interference/electromagnetic compatibility
EU	engineering unit
FMECA	failure modes, effect and criticality analysis
GM	General Motors
GPHS	general purpose heat source
GRC	Glenn Research Center
IN718	Inconel 718
JPL	Jet Propulsion Laboratory
LM	Lockheed Martin
MTBF	mean time between failure
MTI	Mechanical Technology Incorporated

NASA	National Aeronautics and Space Administration
OSC	Orbital Sciences Corporation
POS	probability of survival
PFF	Pluto fast flyby
QA	quality assurance
RGA	residual gas analyzer
RTG	radioisotope thermoelectric generator
SBIR	small business innovative research
SDM	system dynamic model
SIC	system integration contractor
SIPS	Stirling radioisotope power system
SPDE	space power demonstrator engine
SRG110	110 W Stirling radioisotope generator
STI	Superconductor Technologies Incorporated
TDC	technology demonstration convertor
TMG	thermo-mechanical generator
TPV	thermophotovoltaic

I. Introduction

Stirling power conversion technology has progressed through several distinct phases of development. The well- known history of Stirling shows that it was patented in September 1816 as shown in figure 1, by the Reverend Robert Stirling of Scotland. The timing is remarkable since it preceded the 1824 publication of *Reflections on the motive power of fire* by Sadi Carnot, and the 1849 formulation of the mechanical equivalent of heat by James Joule, which laid the foundation for the first law of thermodynamics (ref. 1). Two key features made the early Stirling engines attractive in the decades that followed. First, they provided greater efficiency than the steam engines that were in common use. Early published reports documented the efficiency of Stirling engines by measuring the consumption of coal relative to shaft power produced. The second feature was the safety that they provided. A rigorous boiler code to guide the design of pressurized systems had not been developed. Furthermore, a strict quality control system within the steel foundries had not been established, thus allowing the materials used in boilers to vary widely in material properties. This resulted in numerous boiler failures and accidents that posed hazard to personnel as steam engines were in wide use. The Reverend Stirling was motivated to

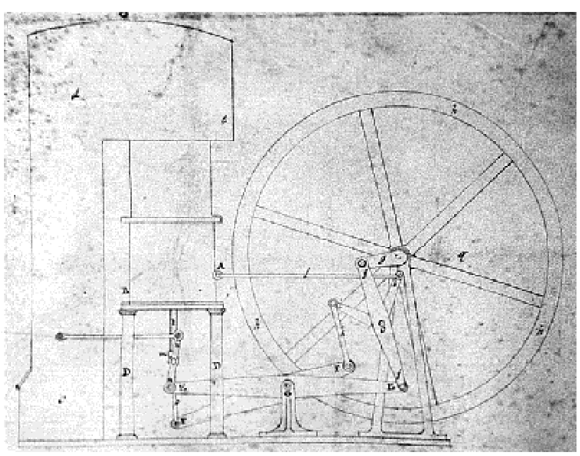


Figure 1.—Drawing from the 1816 patent of the economizer. *The original patent was for the economizer, which operated in the closed cycle engine.*

work on his engine in part due to the concern for the safety of the members of his parish. 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. This was offset somewhat by the lack of a boiler separate from the power-producing cylinder. Stirling engines enjoyed commercial success and were commonly produced in the range of 0.2 to 4 kW (0.3 to 5 hp). John Ericsson developed a variant of the Stirling; an open-cycle regenerative engine that exhausted the working fluid rather than cooling it. A four cylinder marine engine was built in 1853 that produced about 220 kW (300 hp) for use in New York harbor (ref. 2).

Advances in the steel industry resulted in a more tightly controlled product with more consistent material properties. In addition, a rigorous design code was established to guide the use of steel in pressurized systems and enhance safety. The design code used safety factors to provide uniform safety in boilers and piping, and included compensation for the known variation in material properties produced by the steel products of that era. This resulted in relatively safe, high-power steam engines being readily available from numerous manufacturers. Designers were able to push power density of steam engines to higher levels, ultimately resulting in the demise of the Stirling engine. Internal combustion engines were developed by the mid 1800s, followed by the invention of the electric motor later that century. By the early 1900s, the first general phase of Stirling development had ended.

This status did not change until the 1930s when pioneering research began at Philips Laboratories of Einhoven, Netherlands, which dramatically advanced the state-of-the-art. The contributions were in several distinct areas with great impact on performance, the first of which was operating the cycle at elevated mean pressure. An atmospheric Stirling engine moves the power piston back and forth by raising and lowering the working space pressure above and below the surrounding atmosphere. A standard feature of the Philips designs was that they operated at elevated mean pressure, thereby increasing the power density of the engine. 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 it required the working space to be sealed from the crankcase by a seal that could maintain the difference in mean pressure. Several options for linear seals were developed including the rollsock, commonly used by Philips, or the pumping Lenningrader seal later used by United Stirling.

The second major contribution by Philips was the use of gasses other than air as the working fluid. Significant increases in power and efficiency were found to be available in engines with helium or hydrogen as the working fluid. However, the initial interest in low molecular weight working fluids did not come from engine research, rather it came from the development of low temperature coolers, they switched to hydrogen because it offered greatly reduce flow losses, and provided higher heat transfer rates to increase operating speed. By 1954, they succeeded in liquefying air. Both gasses improved performance in engines but presented challenges in containment of the working fluid with hydrogen proving to be more difficult than helium since hydrogen could more easily permeate through polymer o-rings and in some cases, through high-temperature heater tubes.

The third contribution by Philips was perfecting the regenerator to increase cycle efficiency. The regenerator is a porous matrix that absorbs heat from the working fluid when it flows from the hot expansion space to the relatively cool compression space, and returns the heat to the working fluid when it moves from the compression space toward the expansion space. An optimized regenerator will transfer many times more heat into and out of the working fluid during each thermodynamic cycle than the formal heater and the cooler. Philips developed techniques to test and fully characterize the performance of a regenerator, and perfected fabrication techniques of regenerators. It is interesting to note that the early engines developed by Reverend Robert Stirling more than 100 years earlier, had a form of a regenerator known as an “economizer”. This was one of the most important features of the invention, and was likely conceived by intuition. One of the applications envisioned by Philips was a portable generator. The earlier single-cylinder engines had a single crankshaft, but later versions used a dual-crankshaft, rhombic drive mechanism that resulted in linear motion of the piston, displacer, and their supporting rods. This was important as it eliminated side loads and permitted the use of seals to keep crankcase oil out of the

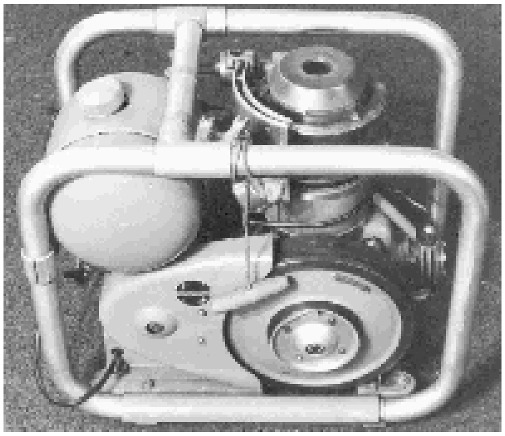


Figure 2.—Philips generator set. *Early generator with kinematic air engine, air pump showing on right.*

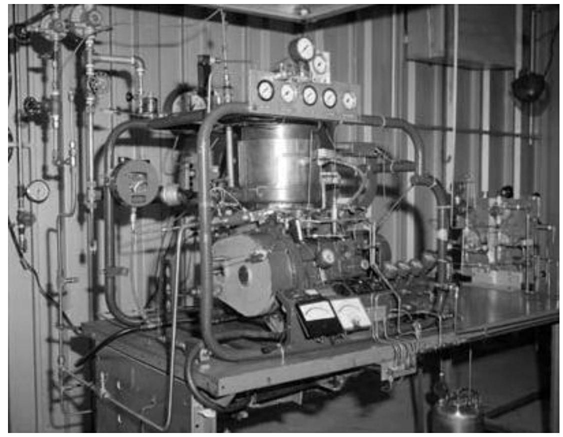


Figure 3.—GPU-3 Under test at NASA GRC. *The GPU-3 was tested with hydrogen and helium to provide data for validation of Stirling cycle models.*

working space and the high-pressure working fluid in the working space. 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. An early generator with a pressurized air engine is shown in figure 2, and the stripped down, rhombic drive GPU-3 is shown in figure 3 being performance tested at the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) (ref. 3). The work at Philips continued into the 1980s resulting in highly developed kinematic engines, which depended on linkages, seals, lubrication systems, and resulted in rotary shaft power output.

GM actively worked on developing Stirling technology from 1958 through 1970 (ref. 4). Their interest dates back to 1947 after reviewing papers that had been published by Philips. They believed that there were applications for the technology for marine applications, particularly for submarine propulsion. 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. They actively pursued applications such as marine propulsion, locomotive power and generator sets, as well as military and space applications. They found no interest expressed by anyone for road vehicle power even though the Philips data showed over 30 percent brake thermal efficiency, and mass that was approaching the Diesel engine. Since Philips had demonstrated high efficiency, GM focused its' efforts on seals, cost reduction, analytical modeling, and combustors. GM received considerable encouragement from the U.S. Army, Ft. Belvoir to develop a Stirling outboard motor and small generator sets which would be nearly silent. The licensing agreement with Philips lasted through 1968, and without having achieved commercial success, development of Stirling technology at GM was terminated by 1970.

One of the applications envisioned for Stirling at that time was an automotive engine. Efforts to develop automotive engines continued at low levels and were often motivated by the multi-fuel capability, quiet operation, low emissions, and increased efficiency. Other features were that the engine needed no muffler, no catalytic converter, there was only one igniter, and there was no need for an oil change over the life of the engine. Interest in the automotive Stirling engine increased sharply in the 1970s, motivated in the U.S. by the energy crisis. The most successful advanced heat engine effort was the Automotive Stirling engine project 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 a four-cylinder engine designated the 4-215 that produced 127 kW (170 hp) and used a swashplate drive mechanism rather than the conventional crankshaft. After approximately 1 year, Ford made a corporate decision to discontinue their involvement in Stirling to focus their resources on a lean-burning Otto cycle engine. 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 Mod II engine, which was a single crankshaft, V-4 configuration (ref. 5). The goals had been achieved of increasing power, reducing manufacturing cost, reduce start-up time, and improve throttle response. Engine efficiency was over 38 percent. A manufacturing study concluded that production cost would be less than a comparable Diesel engine. Early vehicle tests used American Motors Corporation Lerma and Spirit, which logged 2,300 and 13,763 miles respectively. Engines were integrated into three demonstration vehicles, which were put into service, two by the U.S. Air Force and one by the U.S. Postal Service. An automotive Stirling engine is shown in figure 4 integrated into a D-150 pickup truck. The engine resulted in a 10 percent improvement in fuel economy compared to spark ignition engines of the day, with emissions that were lower than the most demanding standards that were being planned. The results of the field trials were positive, with the Air Force van logging more than 1429 hr of operation and over 8,800 miles on JP-4 fuel, Diesel fuel, and unleaded gas. The D-150 pick up truck logging over 1,200 hr on the road, and more than 20,000 miles. The postal vehicle was used in daily service for a 3-month trial. Other technologies advanced during that time and the price of fuel stabilized, reducing the willingness of industry to brace this new technology.

Derivatives of the Philips technology have continued to be developed for applications such as stationary power cogeneration, waste heat utilization, and for biomass systems. The United Stirling technology has also continued to be developed with its' most common use in submarines. Most of the kinematic engines are four-cylinder Rinia engines, in which there are four Stirling cycles operating between the four double-acting pistons. 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; maturing of the kinematic engines.

Although there are references to a resonant Stirling device dating back to the 1940s at Philips, the invention of the free-piston Stirling is accredited to William Beale, founder of Sunpower of Athens, Ohio in the 1960s, when the hardware was first operated successfully. The free-piston Stirling is a resonant device whereby the motions of a piston and a displacer are guided by spring-mass-damping system dynamics. Very generally, the total spring content comes from several sources including internal gas springs, mechanical springs, and other sources of spring that are inherent in the dynamic system, mass comes from the moving physical components, and damping comes from internal flow losses or the load for the power output produced. Development of early free-piston Stirlings focused more on mechanical configuration, dynamics, reliability, and performance, but paid less attention to the conversion of linear motion to electricity or some other useful form of power output. The potential of free-piston Stirling for a range of applications was recognized by the 1970s resulting in the early research efforts for applications

Figure 4.—Stirling engine in D-150 pickup truck. *This truck was put into regular service at several Air Force bases and was driven across the United States.*

such as terrestrial generators, heat pumps, or space power conversion. As the technology was in its' infancy, much of the effort was spent on getting the hardware to operate reliably, as intended, and at full performance. All of these were at power levels of <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 a reasonable amount of development. Integration had improved and the designs were becoming more compact and more efficient. The integrated free-piston Stirling engine with a linear alternator converts heat to electric power and had become known as a Stirling convertor. NASA had interest in Stirling power conversion since the 1970s, envisioning that the technology could 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 would be very difficult to integrate into a space power system due to the mass and complexity of the linkages. The bearings, sliding seals, and other associated mechanisms were all subject to wear, and are therefore life limiting. The automotive engines, for example, had a design life of about 1,000 to 2,000 hr.

The emergence of free-piston 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, shown in figure 5, produced 25-kWe output with conversion of heat to electricity at about 20 percent efficiency when operated at a temperature ratio of 2.0 (ref. 6). It was a symmetrical design with two displacers, two power pistons, and two linear alternators, sharing a common expansion space. The SPDE was a dynamically balanced unit showing negligible vibration. It had hydrostatic gas bearings for non-contacting operation, eliminating any wear mechanisms, thus enabling long life, limited only by the creep of the heater head. It converted heat to electricity at a fraction of the Carnot efficiency, higher than the alternatives. Since it was intended to demonstrate feasibility, the SPDE was built with materials that limited the hot-end temperature to about 630 K (357 °C). The CTPC was then built for similar performance as the SPDE, but with capability to operate at temperatures more representative of a nuclear system. The hot end of the CTPC was designed to operate at 1050 K (777 °C) with the cold end at 525 K (252 °C) with a design life of 60,000 hr. The heater head was designed to be fabricated from Udimet 720, however, due to programmatic considerations, the CTPC was fabricated out of Inconel, which limited the life at the full design temperature. The CTPC generally operated as intended and did not require any

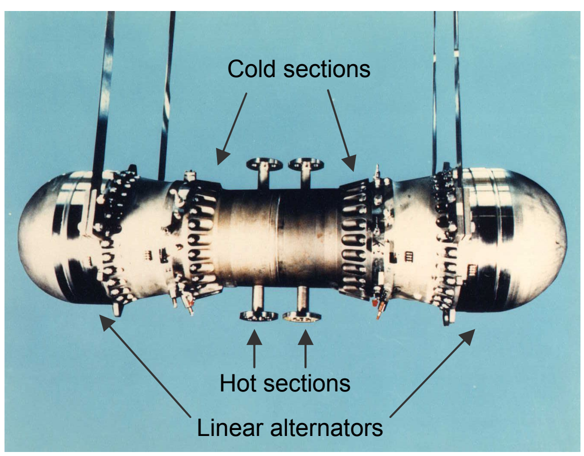


Figure 5.—The Space Power Demonstrator Engine. *The first dynamically balanced, dual-opposed free-piston Stirling convertor with non-contacting operation. Approximately 1.3 m (53 in.) in length.*

additional development effort. When the SP-100 and follow-on Civil Space Technology Initiative ended in the early 1990s, the CTPC had operated slightly more than 1,500 hr.

Other free-piston Stirling convertors were being developed at the same time, often trying to find success in a commercial niche market. Trying to capitalize on the investment being made by the SP-100 project, the Advanced Stirling Conversion System project was conceived to develop a 25 kWe solar-to-electric conversion system. The goal was to develop a system that would be cost competitive as it supplied power to the utility grid, and would include the solar concentrator, solar receiver, free-piston Stirling convertor, and necessary support equipment. The intended life was 60,000 hr over a 30-year period, with one rebuild permitted (ref. 7). It was believed these goals were now achievable by the emergence of free-piston Stirling power conversion which was now sufficiently mature since power levels had reached 10's of kW, efficiencies were high, non-contacting operation had been achieved, and life limiting wear mechanisms had been eliminated by design. Several prototype systems were built and tested, however commercial success was not achieved. The SP-100 convertors represented the state-of-the-art of the technology in the early 1990s. Convertors were being built that were more compact, operated more reliably, and achieved intended performance with minimal development. This can be viewed as a third phase of Stirling development whereby free-piston Stirling power conversion is able to operate at the intended level of performance, albeit sometimes needing a little refinement following initial operation to achieve full performance, but to a great extent still lacking in system integration.

II. Stirling for Radioisotope Space Power

Nuclear and solar thermal power systems in space are generally considered to be in the range of multiple kW's. Radioisotope power systems are commonly considered to be at lower power levels, generally at <1 kWe. Long life and high reliability are the most basic requirements for space power applications regardless of the power level. While feasible, these requirements present a challenge for the use of dynamic power conversion in space. Highly developed kinematic Stirling engines with rotary alternators had been studied for radioisotope space power by General Electric and Philips in the 1970s under contract to the DOE (ref. 8). The Stirling Isotope Power System (SIPS) was designed to deliver more than 1 kWe with system efficiency of approximately 28 percent. Operation was intended to be continuous and unattended for a period of 6 months with only routine maintenance between operation periods. The system was designed for a total useful life of 10 years, with one major overhaul permitted. The engine used the dual-crankshaft rhombic drive mechanism that has timing gears and a minimum of four connecting rods, two rotary alternators, an oil-lubricated crankcase, polytetrafluoroethylene Teflon (DuPont) piston rings in contact with the cylinder, and a "scraper-type" oil seal to keep the oil in the crankcase. The engine, shown in figure 6, was pressurized to approximately 9.53 MPa (1380 psia) with helium and operated at 1950 revolutions per minute. Development of this hardware needed to consider hermetic

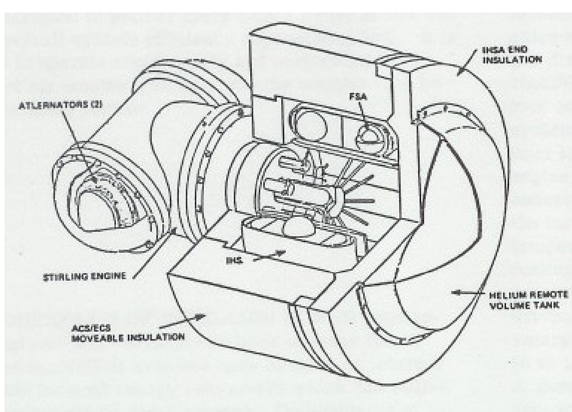


Figure 6.—Kinematic radioisotope Stirling generator. *Stirling Isotope Power System (SIPS) with rhombic drive Stirling and two rotary alternators.*

containment of high-pressure working fluid, isolation of oil from the working fluid, wear of sliding seals, and two-phase fluid management within the lubrication system. There were numerous metallurgical joints in the pressure boundary that consisted of 12 heater tubes, 6 regenerators, and 117 cooler tubes. The heat source provided 3930 W thermal at beginning of mission (BOM) and the nominal operating temperatures were 750 °C at the hot end and 50 °C at the cold end of the cycle. The project resulted in hardware being tested.

With the advent of free-piston Stirling, an alternative became available with potential for long life, high reliability, high efficiency, and reasonable mass. The key features that made it attractive were the elimination of all wear mechanisms by design, 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 GRC to determine the feasibility of free-piston Stirling power convertors in a high-efficiency radioisotope power system (ref. 9). The two systems studied 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 W/kg for the lower power system and 8.0 W/kg for the higher power system. One of the applications for which the generator was proposed was for robotic missions such as planetary rovers. While this was an initial study, lacking some of the details needed in flight development, it did indicate that the concept of a free-piston Stirling radioisotope generator was feasible as a high-efficiency, long-life power generator with a competitive mass. The designs and analyses were refined by subsequent studies that evaluated a range of applications (refs. 10 through 13), and at the conclusion; generators were proposed over a power range of 200 to 600 W power output with specific power ranging from 5.4 W/kg for the lower power level to 8.7 W/kg for the higher power systems. As shown in figure 7, 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 would be nearly balanced dynamically. By the early 1990s the potential had been recognized, however, there were deficiencies in the development that remained to be addressed; 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, "Multi-Hundred Watt Stirling Technology Demonstrator for Space Power," resulted in the design of a free-piston Stirling convertor projected to have 28 percent conversion efficiency with 280 W power output. The design attempted to maintain

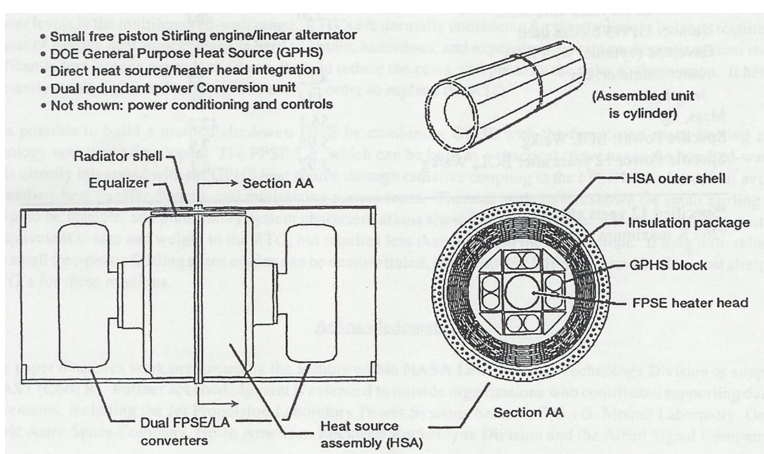


Figure 7.—Generator configuration from 1991 GRC study. *Layout of generator with two free-piston Stirling convertors, each one with two pistons and two alternators to be dynamically balanced.*

efficiency over a wide range of power and achieved 28.4 percent efficiency at half power. The reason for this design feature was that a system might implement 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.

Another effort to study free-piston Stirling specifically designed for the space application was the 1994 study by Fairchild Space and Defense Corporation, performed under contract to DOE (ref. 14). The study made use of designs and analyses of a 75-W Stirling convertor generated by MTI under contract to GRC. Three integrated system options were proposed for a Pluto Fast Flyby (PFF) mission. The PFF mission requirements 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 from 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. One conclusion of the study was that the Stirling convertors "are less mature, requiring more development, and entailing greater programmatic risk." Similar to the aforementioned SBIR, this effort focused on designs and no hardware was produced. A cross section of the generator is shown in figure 8.

Although studies such as the ones performed at GRC indicated feasibility and desirable features in a free-piston Stirling radioisotope generator, the Stirling convertor with the necessary features did not exist. The state-of-the-art at that time had shown operation of 1,500 hr on the CTPC at the 12-kWe level, and 1,100 hr on Engineering Model (EM) Number 2, a nominal 3-kWe free-piston Stirling (ref. 15), both efforts under contract to NASA. The EM, endurance tested in 1983, had hydrostatic gas bearings on both the piston and the displacer and a saturated plunger linear alternator. Some rub marks were visible at the conclusion of the testing, however, the EM had undergone over 250 start/stop cycles as part of the test plan.

By the mid-1990s, conceptual designs had been generated for Stirling convertors for a radioisotope generator, yet there were no convertors under test. Following termination of the SP-100 and the NASA Civil Space Technology Initiative, there were no focused efforts funded by the government to develop the

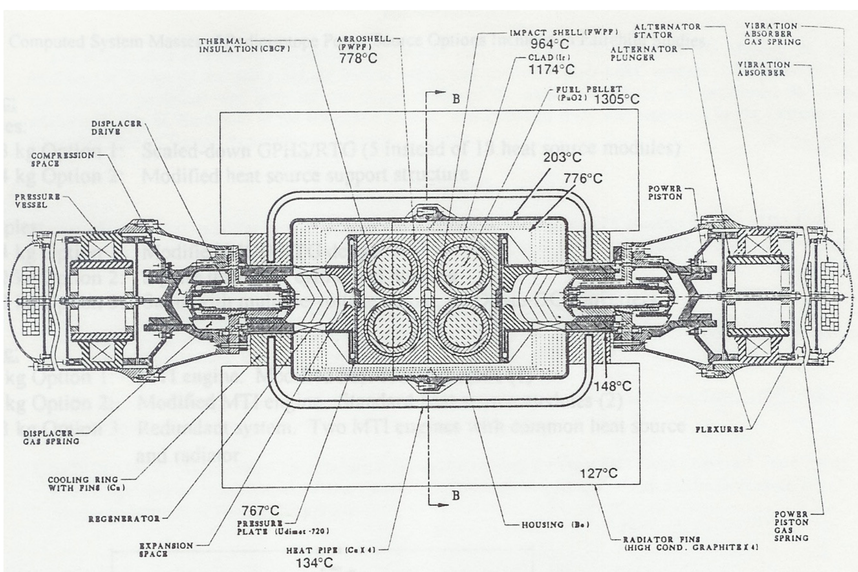
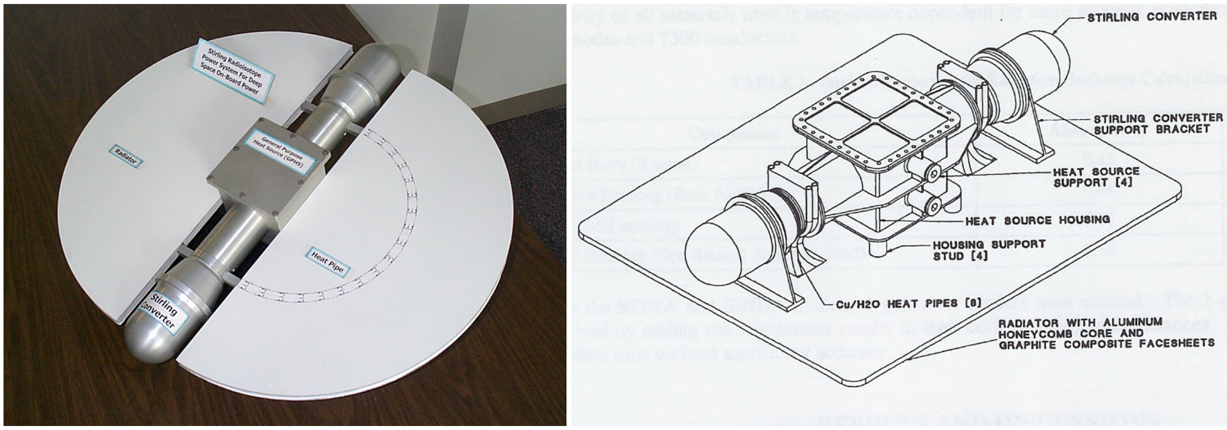


Figure 8.—Stirling generator from 1994 Fairchild study. *Configuration with two free-piston Stirling convertors, each one with a dynamic balancer, sharing four radiator panels.*

technologies necessary for a free-piston Stirling radioisotope power system. Development of relevant technology came from small contracts for similar applications and from SBIR contracts. One example was Phase II SBIR by Infinia entitled "Innovative Integration of Long-Life High Efficiency Thermal Convertors Using Proven Free-Piston Stirling Machines" reported in 1999. The effort dealt with interconnection of multiple free-piston Stirling convertors using a single analog controller with tuning capacitors used to correct the power factor. The project's final report is commonly referred to as the Multi-Engine Generator Study, or MEGS Report. The MEGS SBIR effort involved analytically simulating a number of different dual-opposed configurations with a linear model and comparing the results with test data. Both the analytical studies and the test data included steady-state data and transient response data taken by making and breaking the parallel electrical connection between two alternators. The report identified a system with two convertors connected to one controller, and with the alternators connected in parallel after the tuning capacitors as the most robust and stable configuration (ref. 16). This effort was significant since it was the first demonstration that a power system could use multiple Stirling convertors, each one thermodynamically isolated from one another, and operate with the pistons synchronized for dynamic balancing. This configuration differed from the SPDE, which had previously demonstrated synchronized, dynamically balanced operation of two power pistons but used a single, common working space. Loss of the working fluid, or any other failure in the SPDE would result in both power pistons stopping. This was done purposely on the SPDE to prevent one piston from moving if the other piston had stopped. With multiple convertors synchronized per the findings of the MEGS study, loss of working fluid in one convertor would not inherently force the other convertor to stop, which was believed to be a good feature on the relatively small radioisotope power system. Furthermore, operation was studied in the MEGS project with significant imbalance between the two convertors, yet it was found that stable, synchronized operation could be maintained. Another SBIR at Infinia, the Advanced Vibration Reduction System, addressed vibration reduction beyond that achievable with opposed convertors, along with efforts such as "Adaptive Vibration Reduction Controls for a Cryocooler With a Passive Balancer" at GRC (ref. 17).

Following completion of the GPHS Radioisotope Thermoelectric Generator (RTG) for the October 1997 launch of the Cassini spacecraft, a study was commissioned in to evaluate the developmental status of candidate power conversion technologies for an advanced radioisotope power system. The study was led by DOE and considered technologies such as Alkali Metal Thermal Electric Conversion (AMTEC), Stirling, and thermophotovoltaic (TPV) energy conversion (ref. 18). In general, the report concluded that AMTEC offered attractive features but had risk due to the relatively low developmental status, Stirling was judged an available technology, sufficiently developed to be available for flight development, and that TPV was not sufficiently developed to be considered a viable candidate. DOE initiated the Advanced Radioisotope Power System project and selected Lockheed Martin (LM) of Valley Forge, Pennsylvania, as the System Integration Contractor (SIC) and Advanced Modular Power Systems of Ann Arbor, Michigan supplying the AMTEC cells.

At the same time, 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 >20 percent from heat input to AC electric power output. The TDC had a mass of about 6 kg with anticipated mass reduction if flight development were undertaken. In support of DOE, Orbital Sciences Corporation (OSC) investigated several generator designs to assess feasibility of the integrated system (refs. 19 and 20). Some concepts included three GPHS modules and four Stirling convertors such that each convertor would operate at derated power, and in the event of failure of one convertor, the remaining three convertors would change their operating points to allow the generator to maintain full power. A model of one concept is shown in figure 9(a), which includes two GPHS modules in an insulated housing, two TDC's in dual-opposed configuration, and radiator panels with integral heat pipes. Figure 9(b) shows the self-supporting concept investigated by OSC that was projected to be 16.1 kg and achieve specific power of approximately 8 W/kg (ref. 21).



a) generator with circular radiator panels b) self-supporting generator with flat radiator

Figure 9.—Orbital Sciences Corporation generator design.—*Model of a generator proposed by OSC with two GPHS modules and two early TDC Stirling convertors on left, and image of self-supporting generator with flat plate radiator on right.*

The status of free-piston Stirling for potential use in a radioisotope power system in space had changed measurably by mid-1999. Some of the features previously identified as “potentials” were demonstrated. A 10-W convertor based on non-contacting operation had operated for over 50,000 hr at Infinia with no change in performance. The convertor operates to this day and has accumulated over 93,000 hr (ref. 22). The study led by DOE had identified the Stirling convertor as the “low risk” power source, available with “a dependable background of materials, lifetime, and demonstrated performance” to support upcoming NASA deep space missions. Multiple convertor operation and 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 set for mass. Under contract to DOE for the 55 W TDC, Infinia successfully demonstrated power of over 55 W, and efficiency of over 27 percent with non-contacting operation through the use of flexures, similar to those in use on their 10 W convertor. Due largely to the efforts of the Air Force Research Laboratory (AFRL), Stirling crycoolers had been developed by multiple suppliers that were flight worthy. Approximately 9 Stirling cryocoolers had been placed in flight by 1999 with some relevant technologies used that enabled long life, thus a highly relevant database was being established. Little was known about radiation tolerance, and virtually nothing was known about electromagnetic interference and electromagnetic, compatibility (EMI/EMC), flight controller design, and survivability of launch vibration.

Development of the AMTEC generator was discontinued in 1999 as it was being developed for a specific mission but fell slightly short of the efficiency requirements. A joint DOE/NASA/industry team was commissioned by senior management at NASA and DOE to assess the readiness of Stirling power conversion technology to transition into formal flight development. The study team included DOE-Germantown, NASA GRC, the Jet Propulsion Laboratory (JPL), OSC, LM-Valley Forge, and LM-Denver. A meeting was held in which the key issues were identified that needed to evaluated to determine the readiness. It was the consensus of the team that testing was needed to characterize 1) dynamic launch load capability, 2) EMI/EMC, and 3) performance mapping. Evaluation was needed for 4) radiation survivability of the organics, 5) controller functionality and survivability, 6) a failure modes effect and criticality analysis (FMECA) of the Stirling convertor, and 7) a fault tolerant system configuration was needed. A 3-month study ensued to assess the technology readiness with the tasks divided among the team members (ref. 23). TDC’s nos. 1 and 2 were used for launch vibration testing and EMI testing at GRC (ref. 24), and performance mapping was performed at Infinia. Radiation survivability was evaluated by GRC with supporting expertise from JPL, and a conceptual design of a controller was developed by LM-Denver. A FMECA was prepared by GRC with support from Infinia, and two concepts were

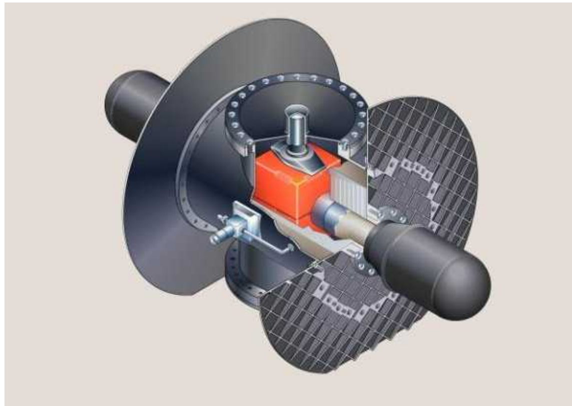


Figure 10.—Radioisotope generator proposed in the 1999 Technology Readiness Assessment. *LM design showing GPHS modules in the center, two TDC's to convert heat to electricity, and combined structure and radiator.*

proposed that fulfilled the JPL requirement for a fault tolerant system. Based in part on relevant information from flight cryocoolers and the long life that had been demonstrated by the ongoing operation of the 10 W convertor at Infinia, it was determined that the TDC was capable of transitioning to flight development.

Status of the technology had changed once again by early 2000. Some of the key issues were addressed by compiling and evaluating existing information, as in the cases of radiation survivability, controller functionality and the FMECA. Integrated system configurations were proposed as shown in figure 10, which considered more of the details than may have appeared in previous concept studies (ref. 25). 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 g^2/Hz) with the TDC operating at full power. The TDC survived the vibration test at the JPL qualification test level used for input into a generator, and then operated for more than 40 hr afterward, before being disassembled for post-test inspection. The inspection showed no signs of wear or damage that was believed to come from the recent tests. Since a detailed generator design did not exist, which might show amplification or attenuation of vibration input, the team decided that the TDC would be tested to the generator vibration specifications.

III. The 110 W Stirling Radioisotope Generator

Based on the findings of the Technology Readiness Assessment, senior management at NASA and DOE authorized the development of a 100-W class Stirling radioisotope generator (SRG110). Three contracts were let by DOE in August 2000 for the conceptual design of the SRG110 generator based on the Stirling convertor developed by Infinia. JPL assisted in developing the specifications for a generic radioisotope power system for deep space science missions. The goal was to develop a generator in response to a generic set of specifications that were representative of the requirements of a deep space mission. The generator could then be tailored through the use of a mission kit to meet requirements that are unique to a particular mission, such as high radiation tolerance or low EMI. Each mission kit may result in a penalty, such as reduced power or increased mass, but the trade would be the prerogative of the particular mission. The specifications called for the generator to be as small and low mass as possible while maximizing specific power at the end of mission, with a multi-year life requirement suitable for deep space science missions. Notional requirements were established for radiation tolerance, EMI, magnetic field, and exported vibration. The designs were initially requested for operation in deep space;

however, a modification to the requirements was issued, asking for the designs to include operation on the surface of Mars. LM was selected as the SIC and flight development of the SRG110 began in May 2002. The contract covered the design and fabrication through an Engineering Unit (EU), with options for a Qualification Unit and Flight Units. The initial design presented by LM enclosed the two GPHS modules and two Stirling convertors inside a beryllium structure that acted as the radiator and provided protection from micrometeoroids (ref. 26). By placing the Stirling convertors inside the beryllium structure with their alternators towards one another, there were two separate high-temperature zones, each one with a GPHS module and the hot end of a Stirling convertor. This concept could tolerate shutdown of one Stirling convertor without necessitating shutdown of the other for thermal reasons, since each Stirling convertor would receive the heat from one GPHS module regardless of the operation of the other convertor. 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 BOM and was 27 kg in mass, for a specific power of approximately 4.2 W/kg. Development continued with LM refining the design of the generator and Infinia refining the design and manufacturing of the Stirling convertors.

Prior to selection of the SIC, NASA established a supporting technology effort at GRC to enlist personnel with experience in the development of Stirling convertors. The effort was tailored to address many of the key aspects of the Stirling convertor and its integration into a generator, all of which were common among the competing system designs. Since the technology effort was chartered to support flight development and not conduct basic research, all of the tasks ultimately contributed to some form of risk reduction. The GRC effort had focused activities in materials, both metallics and organics, structures, lifing analysis and testing, Stirling convertor and controller testing, magnets and linear alternators, launch environments, EMI, and reliability (ref. 27). Following selection of LM as the SIC, the GRC technology effort became a part of the SRG110 project, forming the team of LM, Infinia and GRC. JPL continued to provide guidance on spacecraft integration, mission requirements, processing and generally represented the potential end user since the project was purposely not directed at a specific mission. The design of the EU matured and provided influence on the design of the Stirling convertor as considerations of system integration and flight hardware production were addressed. The SRG110 EU represents the most comprehensive design ever produced of a Stirling radioisotope generator. With some of the requirements having been expanded since the beginning of the project, the best engineering estimate of the generator projected 116-W power output at BOM based on 496 W of heat input from 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 11 shows an image of the SRG110 generator at the time of the EU design review and figure 12 shows the TDC with the mechanical interfaces labeled.

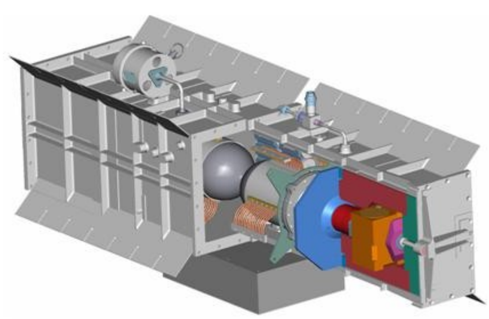


Figure 11.—SRG110 generator with dual-opposed Stirling convertors. *Stirling convertors are located with hot ends away from one another to eliminate fault propagation.*

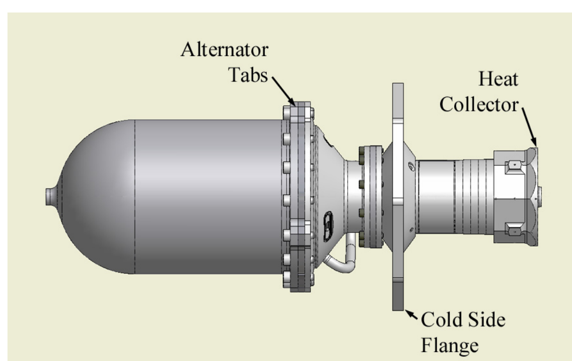


Figure 12.—TDC showing the mechanical interfaces. *Final version of the TDC with hermetic sealed flanges and thermal and structural interfaces labeled.*

As a result of the SRG110 flight development project, the status of free-piston Stirling power conversion changed 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 of the Stirling convertor, the major efforts currently deal with system integration. Some of the more significant advances with general applicability to long-life Stirling convertors will be briefly described.

A. Materials

1. Metallics

The heater head is a critical component in achieving long life of the convertor since it is a pressure vessel that that has been optimized to reduce conduction losses. A thin wall benefits performance since it minimizes conduction losses; however, the design trades generally make the wall as thin as possible, resulting in creep of the heater head over time, while achieving the design life with the necessary margin. In a convertor that has had all wear mechanisms eliminated by design, creep of the heater head would be the only effect known to continue with time. 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 deterministic and probabilistic analyses, material testing, and an extensive long-term creep and creep-rupture database with 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 walls. Long-term creep testing was then performed of two purchases of IN718. The maximum time on a single test specimen is 41,600 hr, as of June 14, 2006, at a stress level of 414 MPa (60 ksi) and a temperature of 593 °C. The structural benchmark tests were used to factor in the biaxial stress state and validate the analysis. The analysis was based on probabilistic techniques that project Probability of Survival (POS) of the heater head over the life of the mission. This technique considered uncertainties and variations in the material properties, the heater head geometry, and the convertor operating conditions. End of life was 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. 28).

The analysis was compared by 1-, 3-, and 6-month accelerated structural benchmark tests of heater head pressure vessels, where increased pressure levels were used to increase the creep rate. Two tests with tapered-wall pressure vessels were run at the convertor design operating pressure; not accelerating the creep rate. All tests were run at 650 °C in the critical area at the hot end of the regenerator, however; life can be extended by reducing the temperature. Through the SRG110 project, lifing analysis was refined for the only component that can limit the life of the Stirling convertor by aging. With some 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 superalloys.

The regenerator is a porous matrix of metal fibers that is a critical heat exchanger in the convertor. Regenerators are commonly made from a matrix of random metallic fibers that are sintered together. These fibers have often posed a concern with respect to reliability as it is thought that some fibers may become detached from the matrix during operation resulting in diminished thermodynamic performance of the regenerator or possibly traveling to a critical location that cannot tolerate the physical presence of the fiber. Fiber shedding has been observed in operating convertors, however it has been 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 by varying time and temperature. Sintering schedules were evaluated by optical inspection, tensile tests, and by observing the amount fibers that were shed over time when the regenerator is cleaned in an ultrasonic cleaner. It was found that regenerators could be made with no fibers being shed under continued testing by using with an optimized sintering process followed by a controlled cleaning process.

2. Organics

Organic materials are used in limited amounts in the Stirling convertor, primarily in the linear alternator. The organic materials are used for electrical insulation, structural bonding, and as a surface treatment in the close clearance seals where there might be temporary contact of moving parts. Organics were a concern in the SRG110 project in terms of 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 recommended based on the time-temperature-transformation characteristics, and by evaluating lap shear adhesive 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 standard room-temperature cure cycle. A systematic thermal-physical-structural evaluation at various temperatures showed that the epoxy was stable up to temperatures of 180 °C. Short-term accelerated aging tests of the epoxy (cured with the standard room-temperature cure cycle) were conducted for up to 150 days at 150 and 180 °C. No degradation in the epoxy was observed and the epoxy showed substantial increases in lap shear adhesive strength at 80 and 120 °C after aging at these time and temperature conditions. The most recent efforts addressed the application of the knowledge gained to the production hardware.

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 (0.06 in.) aluminum, this level of radiation, or that there were substitutes readily available. Radiation tolerance for missions such as Europa, which could reach 4 Mrad (Si) behind 2.5 mm (0.10 in.) aluminum, would require a mission kit as mentioned earlier.

Outgassing of the organics was a concern as it might indicate decomposition of the organic, and the gas generated could deposit or react chemically with some of the internal components. The small amount of non-helium in the working fluid would likely not be sufficient to affect the net properties of the working fluid and the thermodynamic cycle. One of the features of the convertor test procedure at GRC was the ability to sample the helium working fluid during extended operation tests. A manifold system was developed and connected to each convertor through which a small amount of the working fluid could be sampled and analyzed by a Residual Gas Analyzer (RGA). The manifold used orbital welded connections wherever possible and the Stirling convertors were hermetically welded during some of the tests, with the exception of the helium fill tube. The fill tube was purposely not pinched and sealed, so that gas samples could be analyzed during the test. More than 80,000 hr of operation have been accumulated with nearly 22,000 hr on TDC’s nos. 13 and 14, and over 7,000 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. Techniques used to bake out components during fabrication, and to bake out the final assembly have been found to be important. Components and subassemblies are limited by their unique features and materials, and are must be integrated into the assembly process. Lessons from the cryocooler industry can be directly applied to power convertors. 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, the long life Stirling cryocoolers in terrestrial application, and operating experience at GRC, it appears that outgassing or decomposition of the organics in a Stirling convertor does not pose a problem.

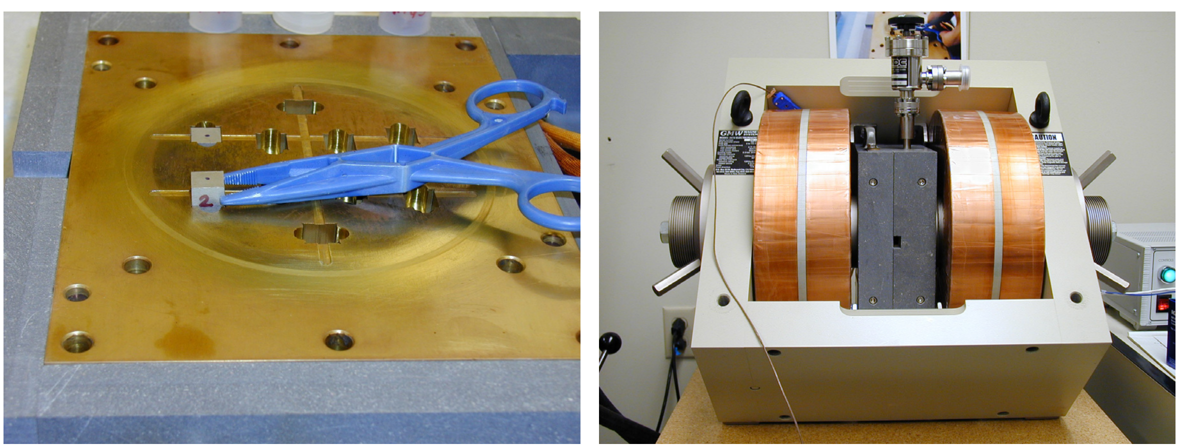
B. Magnets and Linear Alternators

Long life and reliable performance of the convertor requires the permanent magnets of the linear alternator to maintain their magnetic properties throughout the mission. Characterization tests were performed on 1-cm cubes of candidate magnet material obtained from various vendors. All samples were neodymium-iron-boron rare earth permanent magnets. The remanence, intrinsic coercivity and the magnetization were measured for each of the magnet 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 the characterization, the preferred magnet types were selected for a short-term aging test that lasted 200 hr, with the samples exposed to a demagnetizing field of –5.0 kOe and maintained at 150 °C. The test hardware for magnet aging tests is shown in figure 13. This demagnetization field and temperature were far in excess of what was expected in the SRG110 application. 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 demagnetizing field of –6.0 kOe at 120 °C. This demagnetization field and temperature were once again in excess of the SRG110 operating conditions; however, they were not as severe as was used in the short-term aging test. The long-term magnet-aging test lasted for 18,000 hr (ref. 29). These tests were intended to characterize the magnets, to provide data so that the design of the alternator could be optimized in terms of performance with adequate operating margin. 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.

The aforementioned tests characterize the magnet material. With a rectangular magnet, the magnetic field measurements taken outside of the magnet are used to project the properties within the magnet. However, the techniques used to characterize the material of a rectangular cube cannot be directly applied to a curved magnet as would be used in the alternator. A magnet paddle for characterizing curved magnets was developed at GRC and the 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 could predict either two-dimensional or three-dimensional stress states within each magnet. The analysis was validated by demagnetization tests performed at Infinia and at GRC, in which the linear alternators were operated at increasing temperatures until demagnetization was sensed. In all cases, the analysis and data agreed within the measurement accuracy and variances of the magnet material properties.



a) magnet sample being installed b) fixture located in electromagnet

Figure 13.—Magnet test hardware at GRC. *A magnet sample being placed in the aging fixture, and the magnet aging fixture installed in electromagnet for an aging test.*

C. Structural Dynamics and Launch Environments

The ability of a Stirling convertor to survive launch loads while mounted in a generator was unknown when the Technology Readiness Assessment prompted the 1999 vibration test of TDC no. 1. Only the Stirling convertor was vibration tested at that time since there was no definitive design of a generator housing or mounting structure. The Stirling convertor was tested up to 12.3 g (0.2 g^2/Hz), which was the level specified for input to the generator. This test made no assumptions about the amplification or attenuation that the generator housing and mounting structure might provide.

Since that time, 6 additional vibration tests have been performed on relevant Stirling convertors, including transmissibility tests to investigate integration of convertors into a generator, modal tests to study response of the Stirling convertor, and tests of operating convertors to verify design changes. The SRG110 generator design evolved, based in part on results of these tests and launch load considerations (ref. 30). Two significant design changes were made to the generator relative to the baseline design. First, the Stirling convertors were connected to one another structurally at the aft end of the pressure vessels. Without this feature, each convertor could rotate independently about their respective cold flanges during launch vibration. The cold flanges serve as the mounting structure between the Stirling convertors and the generator housing. With the structural connection between the two convertors, the moment of one convertor can react against the other convertor, eliminating significant rotation. The two convertors act as one single, cylindrical structure, mounted to the generator housing by the two heat rejection cold flanges. This is illustrated in figure 14, showing an example of the response of the baseline design compared to the response with the connecting tube.

The second change was the development of a compliant spacecraft mounting interface structure. Significant reduction in the dynamic response of the convertors resulted from the use of the compliant launch adapter. The interface is similar to interfaces used in the past on GPHS RTG missions, however past designs were driven primarily by thermal considerations, whereas this design was driven primarily by structural dynamic considerations. A finite element model of the generator housing and the Stirling convertors was used to determine the response of the most critical components. The interface was then designed to achieve fundamental modes between 35 and 50 Hz in the axial and lateral directions for attenuation of the vibration input.

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. Operating TDC's were not used in this test; rather, mass models of the TDC's were mounted inside a cylindrical housing that simulated SRG110 generator assembly. The TDC mass

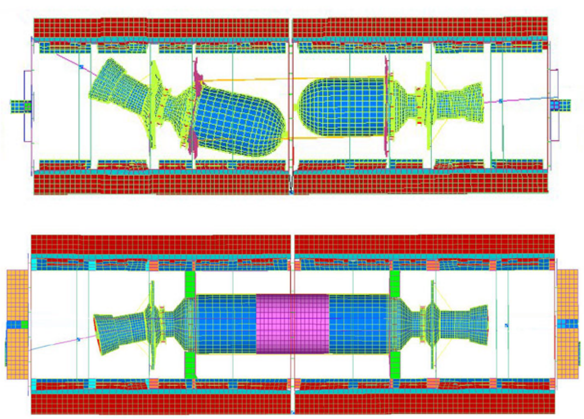


Figure 14.—Comparison of response of Stirlng convertors. *Baseline mounting configuration shown at top, and improved mounting configuration shown at bottom.*

simulators were assembled with components used in previous TDC builds or available for future builds, and thus provided very accurate mass models of operational Stirling convertors. They were connected to one another by a common pressure vessel rather than the two separate pressure vessels and connecting tube, as shown in figure 15. The TDC's were pressurized throughout the tests, as they would be while being operated. The generator simulator was an aluminum tube designed to have appropriate dynamic characteristics representative of the SRG110 beryllium housing. Mass models of GPHS modules were positioned between the ends of the generator housing and the heater heads, as they would be in the actual generator, thus providing realistic loading on the generator and the Stirling convertors. The spacecraft interface was simulated by a set of flexure blades that were sized to achieve the same dynamic response of the actual spacecraft interface. Final sizing of the blades was verified by testing on the shaker table. Tests were conducted with the flexure blades representing the spacecraft interface, and with the generator simulator mounted directly to the shaker table. The generator simulator mounted rigidly to the table and with flexure blades is shown in figure 16.

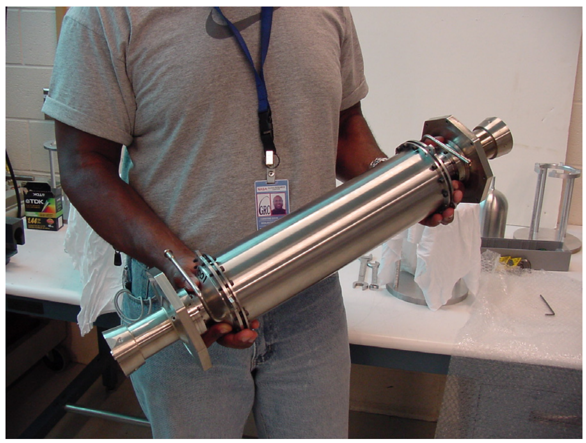
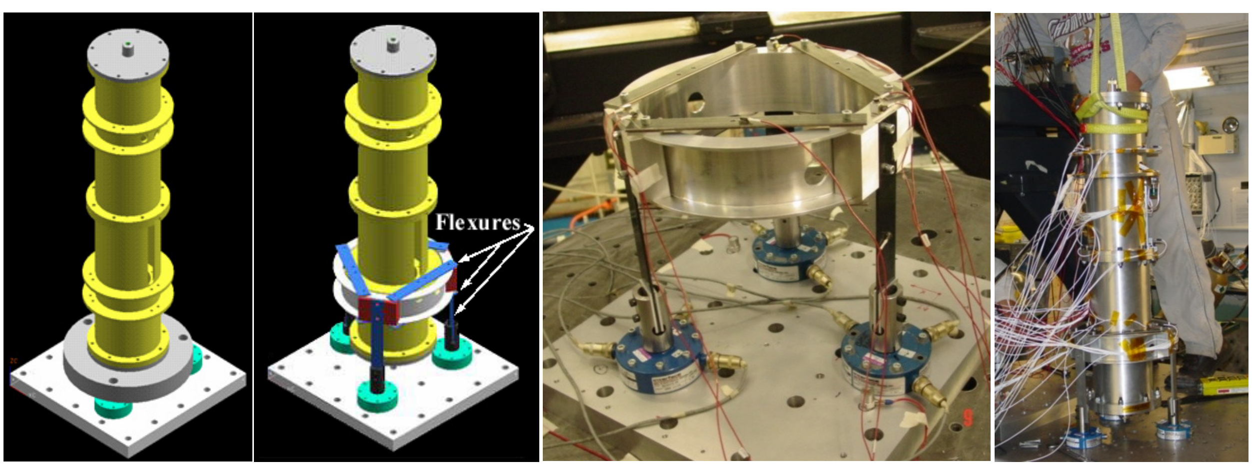


Figure 15.—TDC mass simulators attached to a common pressure vessel. *Stirling convertor heater heads and cold flanges outside of each end of the pressure vessel.*



a) hard mounted b) on flexures c) flexure test hardware d) generator

Figure 16.—Generator simulator test images. *Generator in (a) hard mounted test configuration, (b) mounting with simulated spacecraft interface, (c) interface hardware simulator, and (d) generator simulator assembled with spacecraft interface simulator, being mounted on shaker table.*

Tests were run up to 15.1 g (0.3 g^2/Hz), and data from the generator simulator test confirmed the analytical predictions. The high response by rotation of the Stirling convertors was essentially eliminated by connecting the convertors together in one subassembly, mounted inside the generator housing. The preload needed on the GPHS modules located between the ends of the generator housing and the heater heads, was maintained throughout the test. The data indicated that the response of components was generally as predicted by the pretest analysis. This test demonstrated the feasibility of using a spacecraft interface mount with tuned isolation as a viable method to reduce the response of the generator and the internal components. Response with the spacecraft interface mount was between two and nine times lower than with the hard-mounted configuration. The test results indicated that the generator simulator, mounted on the spacecraft interface could withstand testing to a level of 15.1 g (0.3 g^2/Hz), and that all of the component responses, including those of the Stirling convertors, would be within the allowable stresses of the components of a Stirling convertor tested to 12.3 g (0.2 g^2/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 g^2/Hz had been demonstrated, with analysis indicating the capability to survive up to 0.3g^2/Hz.

D. EMI/EMC

Compared to other areas, less development has been undertaken to understand sources of EMI and reduce the emissions from Stirling convertors. This is due in part, to EMI being an integrated system issue rather than it being a requirement that can be levied on a component or a subsystem. This is also due in part, to the generic set of requirements that have been placed on the SRG110 generator, with the approach being that requirements for lower levels of EMI would be considered a mission kit, and responsibility for developing the capability would be placed on the mission office from which the more stringent requirement originated.

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 if such a mission kit were needed. 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 on a TDC to investigate electric and magnetic field emissions and methods to reduce the emissions.

In the 1999 test, GRC and JPL measured emissions from TDC nos. 1 and 2 in the GRC EMI/EMC facility. The purpose was to measure radiated emissions to determine compatibility with the X2000 requirements, which are up to 100 dB more stringent than the Mil-Spec 461E requirements. These levels were derived from the planned Europa Orbiter, Pluto Kuiper Express, and Solar Probe missions being planned at that time. Tests included AC magnetic emissions from 50 Hz to 150 kHz, search coil measurements at 25 cm and 1 m, electric field emissions from 50 Hz to 150 kHz and from 14 kHz to 1 GHz at 1 m, characterization of the controller current and voltage waveforms, and magnetic field emission measurement using partial coverage by mumetal shields over the alternators (ref. 24). 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. 23).

The 2001 magnetic field characterization test was conducted at GRC to aid in understanding the field strength and emissions of the TDC, and was then used to development an initial strategy for emissions management. The tests used TDC's nos. 5 and 6, and it was found that the complexity of the radiated magnetic field distribution resulted in a variance of ±6 dB at 50 cm. The emissions were found to be symmetrical from one convertor to the other, and around the axis of each convertor. A substantial difference in spatially oriented peaks and nulls was not identified. Tests were conducted with two controllers, one having a zener diode resulting in harmonic content in the current, and the other being a resistive load resulting in very little harmonic content. The emissions did not vary greatly between the two controllers. The TDC alternator fundamental frequency measurement suggested an AC magnetic field emission on the order of 110 dBpT at a 7 cm distance, which is significantly below the maximum allowable by MIL-STD-461E, and the data taken during this test supported this assumption. A test of the stainless steel pressure vessel showed that it provided very little attenuation of radiated magnetic emissions, and it was suggested that the pressure vessel could be replaced by one incorporating a hi-mu material for an estimated 40 dB reduction in radiated magnetic field.

The 2005 test conducted at JPL with TDC no. 7 was intended to measure the magnetic and electric DC and low-frequency emissions, determine if they were compatible with science needs, and determine if the emission levels could be further reduced. This test was perhaps the most comprehensive test among the three mentioned. It was found that electric field conducted emissions were compatible with most flight instruments. The low-frequency electric field tests showed emissions from 3 to 10 kHz due primarily to unshielded cables, and that the emissions were below the levels set by most flight instruments. Low-frequency magnetic field emissions were measured from 0 to 20 kHz and it was found that the emissions were dominated by the 80 Hz operating frequency, and that 0.5 mm (0.020 in.) 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 overall conclusion was that while the emissions were higher than desired with the basic TDC, the 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-like generator has been assembled and tested. Furthermore, since the EMI/EMC requirements can vary greatly, depending on the mission, there will always remain question about how low the emissions can be. Data from the three tests tends to indicate that low levels can be achieved that are sufficient for most science missions; however, there will likely be some mass penalty if shields need to be added.

E. Reliability

Perhaps the most basic requirement for a radioisotope generator for space power is reliability. It can be argued that most all of the effort expended by LM, Infinia, and GRC in the SRG110 effort was intended to address reliability. Since it is difficult to prove life and reliability of a device that has had the wear-out mechanisms eliminated by design, the reliability effort was multi-faceted. It included classic methods such as FMECA, reliability block diagrams and fault tree analysis. Probabilistic techniques were applied to many of the critical components including the heater head, the linear alternator, the flexures, and the fasteners. Extended operation tests were conducted primarily to investigate life and reliability. Lastly, the wealth of experience that has been accumulated by long-life cryocoolers in both terrestrial and space application was studied to find relevant information.

A FMECA of the TDC was constructed early in the SRG110 project by a team from Infinia, LM and GRC. Some items were determined to have relatively high criticality, and development plans were established to retire risk associated with those items. None of the items was found to be fundamentally lacking in development for the long-life application. Most of the items were addressed by activities performed at Infinia and resulted in updates to the process and inspection procedures, ultimately improving the quality control. This is similar to the experience of the long-life cryocooler industry, which has found that multiple designs of long-life cryocoolers exist, yet each design must be produced with great attention to procedures and quality control to achieve long life.

Probabilistic analysis was preformed at GRC on many of the components of the TDC. The first component addressed was the heater head since it is known that this component will creep over time and thereby age. Probabilistic analysis took into account variability in the material property, manufacturing dimensions of the heater head, and the operating pressure and temperature. Analysis of the final design 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 a highly unlikely operating 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. It can be stated that there is extra margin in the life calculation. Probabilistic analysis was then performed on the alternator flexure, the displacer flexure, the linear alternator magnets, the fasteners, and the regenerator. No cases were found in which the life requirement of >14 years was unable to be met with high reliability, assuming that the necessary levels of quality were achieved during fabrication. An effort was established at GRC to combine the individual probabilistic reliability analyses into a single probabilistic reliability projection for the complete Stirling convertor. This is not a matter of multiplying one reliability by another since there can be significant interaction among the components and subassemblies. Details of the methodology have not been completed at this time.

As mentioned earlier, extended operation of the Stirling convertors at GRC was intended to provide data on details of the operation over a long period. The test stands were established with the capability to try to find changes over time, even if the overall performance of the convertor had not changed (ref. 31). One example of this capability is the use of an RGA to monitor the composition of the working fluid. Six convertors have been placed on extended operation at GRC (ref. 32). TDC's nos. 13 and 14 have accumulated nearly 22,000 hr of operation, TDC's nos. 15 and 16 have accumulated over 7,000 hr, and TDC's nos. 5 and 6 have accumulated nearly 9,000 hr. These tests are not intended to be endurance tests, which typically have a goal of operating until breakage; rather the tests are extended operation over a fixed period. During operation, changes in any measurable features or parameters will try to be sensed, and a post-test inspection will follow operation. It can be summarized that there has been no indication of any changes based on the gas analysis (ref. 32). Some small amounts of contaminants have been detected, however, they have either come from outside atmosphere permeating into the working fluid, or come from known internal sources, such as trapped pockets. After a total of over 79,000 hr of operation, there has been no indication if any outgassing from internal materials or decomposition of the organics. More than 2.3×10^{10} cycles have been accumulated during these tests with no failures other than facility support equipment. Four of the convertors at GRC were hermetically sealed; TDC's nos. 13 and 14 following 19,000 hr of operation, and TDC's nos. 15 and 16 following 4,400 hr. During this same period, other Stirling convertors have been fabricated by vendors that have been hermetically sealed, as is done with essentially all long-life Stirling coolers. This was not the case in 1999, when there were few if any examples of hermetically sealed, long-life Stirling power convertors.

It should be noted that 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 power convertor. One might accelerate the life of the heater head by raising the charge pressure, and therefore the stress level to increase the creep rate; however, this same mechanism will not accelerate the life of other components. Degradation of the organics in the linear alternator is driven primarily by temperature, and degradation of the magnets in the alternator is driven by a combination of temperature and magnetic stress. Accelerating the life test of a flexure may be accomplished by increasing operating frequency, yet even this must be done with care since the harmonics of the component may change at different operating frequencies. As has been found with long-life cryocoolers, there is no single mechanism for accelerating the life of the assembled unit, and life must be demonstrated by a combination of component tests, some with accelerated life and others to validate analytical models, and extended operation tests.

F. Controller Development

In 1999, there were no designs for a flight controller. A flight controller must have high reliability over the life of the mission, and be able to operate in an autonomous manner, in addition to meeting specific requirements of a mission such as operating temperature and radiation tolerance. Since that time, there have been fully autonomous controllers designed for space and terrestrial applications, however, none of the designs for space have been built and tested. Results of the designs have indicated that a flight-worthy controller is possible, yet none exists and therefore, none of the extended operation tests is making use of a flight-like controller.

An advanced controller is presently being developed at GRC that will make use of active power factor correction (APFC) to eliminate the need for 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.

IV. Other Relevant Sources of Data

A. Long Life Cryocoolers

A valuable source of data that is relevant to life and reliability of Stirling power convertors has become available through the emergence of long-life, free-piston Stirling cryocoolers. These coolers can be found in many applications; however, the greatest sources of data are space flight, and cooling of super conducting filters in the telecommunication industry. The data is highly relevant since these applications require continuous operation, very often in demanding environments, with the life measured in years, and require reliability that cannot be compromised. The data is also highly relevant since the linear motor, compressor, and heat rejector of the Stirling cryocooler are identical in many ways to the linear alternator, power piston, and heat rejector of a Stirling power convertor. Kinematic Stirling cryocoolers have been produced commercially for many decades, and free-piston Stirling cryocoolers have been under development for as long as free-piston Stirling power convertors. Initially, Stirling cryocoolers were used in many critical applications, however these were tactical cryocoolers, and a distinction must be made between tactical cryocoolers, which have contact of moving parts during operation and thus have wear resulting in a finite life, and a long-life cryocooler in which there is non-contacting operation and the wear has been eliminated by design. Tactical Stirling cryocoolers are produced by many companies and are in wide spread use in terrestrial scientific and military applications. Stirling coolers with limited life have flown in space beginning in 1971, however, there was often some degradation in performance as a result of contacting operation and wear (ref. 33). The first long-life Stirling cryocooler based on non-contacting design was launched on the ERS-1 spacecraft in 1991. It was a planned 3-year mission, however operation continued for nearly 9 years. There was a concerted effort, primarily led by the Space Vehicles Directorate of the AFRL, to develop long-life Stirling cryocoolers for space applications and develop technology for system integration (ref. 34). In part, because of the AFRL effort, there have been 32 long-life cryocoolers launched on 21 instruments since 1991. Of these, only one was not a Stirling cycle cooler. All of these coolers continue to operate with no degradation with the exception of 1) the mission ending for three of the coolers with no degradation having been experienced, 2) the instrument failed on one mission, and 3) the displacer failed on one cooler. The longest operating unit began service in February 1998, and has accumulated approximately 73,000 hr in space. It should be noted that these numbers reflect usage in civil space applications; it is not known how many cryocoolers may have been used in secure, military applications and how many hours of operation these cryocoolers may have accumulated.

As mentioned previously, there are many similarities between long-life Stirling cryocoolers and power convertors, including bearing systems for non-contacting operation, hermetic sealing, heat exchangers, linear alternators and linear motors, the use of organics, the need to maintain pure helium, and in the controllers. The methods for achieving long life are also quite similar in that a high quality design must be developed, and then a stringent quality assurance (QA) program must be established to eliminate sources of error during fabrication. There are also differences between cryocoolers and power convertors that should be noted. Some of areas of similarities and differences will be discussed.

The most basic requirement for long life is non-contacting operation. The first space flight cooler with non-contacting operation was an Oxford cooler launched in 1991. Non-contacting operation was achieved in this cooler with a compressor assembly supported by flexure bearings and a displacer assembly also supported on flexures. It is believed that 29 out of the 31 coolers mentioned previously used flexures to support the moving components. The most common form of flexure is a flat disk with

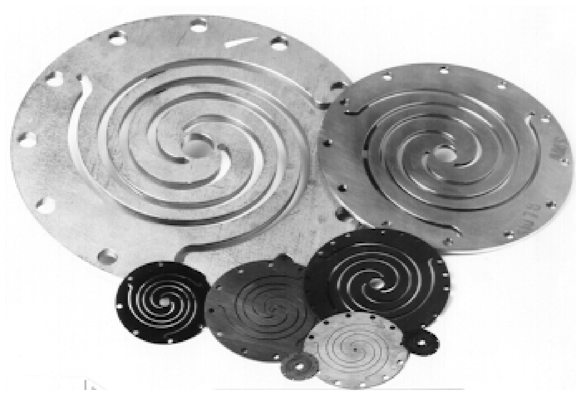


Figure 17.—Examples of flexures. *Slots are used to form spiral arms between an inner hub and an outer ring. Axial and radial stiffness are tailored for the application.*

slots cut to form spiral arms connecting an inner hub to an outer hub as shown in figure 17. The use of flexures in cryocoolers and power convertors is essentially identical. The compressor of a cooler and the alternator of a power convertor operate at about the same temperatures, and the flexures of displacers in both applications operate at similar temperatures. The amplitudes are determined during the design process but tend to be similar. More importantly, long life is achieved by managing the cyclic stress, which can be tailored by design, and applying a set of proven processes through the QA program.

There has been some recent experience with gas bearings to support the moving components. Gas bearings were originally implemented in a Stirling power convertor for space in the SPDE. The SPDE had a system of ports that would use the Stirling cycle pressure wave to pump up a high-pressure plenum, and then use a series of ports to bleed high-pressure helium into the clearance seals between the power piston and the cylinder, and between the displacer and its support. Sunpower developed an improved version of this bearing system that is more efficient yet provides the same non-contacting operation. This gas bearing system is used in all of the long-life cryocoolers produced by Sunpower, and can be found in many of their power convertors, including the ASC. These gas bearings were used in the EE-35 convertors that operated successfully at nearly 24 g (0.8 g^2/Hz) during a 3-min long vibration test. This system was also used in the cooler on the RHESSI spacecraft, which has operated continuously since the February 2002 launch, approximately 38,000 hr, with no degradation.

Long life requires hermetic sealing with generally no loss of pressure during the mission for both coolers and power convertors. In both cases, this is achieved through a hermetically sealed assembly. The number of joints on the pressure boundary is often minimized to improve reliability. There are often electric feed throughs for power flow and for position sensors. A fill tube or fill port exists that must be sealed after the unit is charged with helium. The hermetic seal brazes and joints are qualified and reliability is ensured through the QA process. While loss of pressure often shows as a major concern in a FMECA, experience has shown this not to be a problem. The power convertor will operate with the heater at elevated temperature, which can result in permeation of the helium through the heater head; however, the loss of pressure will be insignificant if designed properly. As an example, the TDC design pressure is 2.5 MPa, (363 psia) and the loss of pressure was determined to be approximately 0.025 Pa (0.0036 psi) by permeation over a 14-year mission.

Power convertors and cryocoolers have similar heat exchangers to transfer heat into the unit and to reject waste heat from the unit. The quantity of heat absorbed by a cooler is very often quite small compared to a power convertor. A cryocooler may lift <10 W, whereas a power convertor for a radioisotope generator will be driven by about 220 W of heat. Waste heat rejected from the two types of units can be similar; however, the heat exchanger of most interest is the regenerator. The regenerator in both cases is intended to increase the efficiency by storing and releasing heat with each cycle. Because of the significant difference in operating temperature, the materials of choice are different. In power convertors, the regenerator material most commonly used is a metallic random fiber structure with the fibers sintered together for structure. The regenerator is commonly between 80 and 90 percent porous with fibers in the range of 20-μm (approximately 0.0008 in.) diameter. Two features of the regenerator are sought to enhance reliability for long-life applications. Reliability could be compromised if the regenerator sheds fibers during operation. To eliminate this, the sintering process is optimized to produce the highest strength structure possible. The fabrication process, including sintering, cutting, cleaning, and installation are controlled through the QA program. Secondly, as a belt-and-suspender approach, it is desirable to use a regenerator material that is resistant to oxidation. This second feature should not be considered necessary. If the convertor is processed properly, will be no sources of contaminants into the helium working fluid, thus, it can be considered a part of the belt-and-suspender approach.

Linear alternators and linear motors perform much the same function with a difference in the direction of power flow. Cryocoolers have generally opted for a moving coil design whereby the coil of copper moves through a magnetic field produced by a permanent magnet and associated iron to manage the magnetic field. The benefit of this configuration is that there are no side forces on the moving component even though, due to the increased size of the copper coil, it can result in slightly greater total mass, increased moving mass and lower efficiency compared to moving magnet designs. In addition, a moving coil alternator or motor requires some method of electrical connection to the moving component, which is generally accomplished through the flexures. Moving coil machines that do not use flexures would require some other form of electrical connection, which could compromise reliability. Power convertors have often opted for designs with stationary coils, but with either moving magnets or moving iron. Most of the cryocoolers in flight are of the moving coil design; however, the cooler on the RHESSI spacecraft is an exception as it has moving magnets. These differences in configuration aside, the linear alternators and motors are essentially the same, and long life has been demonstrated successfully by all configurations when built properly. There have been no problems reported in the structure of the coil, magnet, and iron, and there have been no reported problems with the life of the permanent magnets. Methods to accelerate life testing of the candidate magnets, and design practices that enhance the operating margin of the magnets continue to be investigated.

For rather different reasons, both Stirling cryocoolers and Stirling power convertors try to minimize the use of organics in the linear alternators and motors. If the organics degrade and outgas, the helium working fluid will contain some type of contaminant. In a cryocooler, the contaminant will condense in the cold heat exchanger, thus degrading the performance due to its physical presence on the heat exchanger surface. This has been observed in cryocoolers and can be cured by warming the cryocooler cold finger, and thereby vaporizing the contaminant into the working fluid. This is only temporary since the contaminant will eventually condense once again on the cold heat exchanger when operation resumes. When properly designed and processed, the organics do not contaminate the working fluid and there will be negligible condensation on the heat exchanger. In a power convertor, the contaminants could possibly react chemically with the internal components. The most likely reaction would be any contaminants that contain oxygen, which would be more likely to react with components in the hot end of the Stirling. This in itself is not a problem if components in the hot end are either oxidation resistant by nature of their material properties, or if they are thick enough to be able to build an oxide layer that provides oxidation resistance. In addition, the presence of non-helium in the working fluid is not a problem as relatively large amounts of non-helium can be tolerated in the working fluid before the Stirling cycle is noticeably affected. A test at GRC confirmed this when performance of TDC's nos. 13 and 14 operating with working fluid that contained some residual argon and nitrogen, was compared to performance with a fill of pure helium. The analysis predicted that the change in performance would not be measurable and the test results confirmed this. Furthermore, during the nearly 22,000 hr of operation of TDC's nos. 13 and 14, and during the 7,000 hr of operation of TDC's nos. 15 and 16, the working fluid has been sampled regularly to try to detect any outgassing that may have originated from the organics. To date, there has been no evidence of any degradation of the organics, or outgassing of any form within the TDC's.

There are also similarities between controllers for Stirling cryocoolers and some of the controllers for power convertors. In general, the flight cryocooler controllers receive power from a source that provides direct current (DC) electric power. The controller receives some indication of the operating point of the cooler, creates, and flows alternating current (AC) to power the cooler with the correct amplitude and sometimes a stipulated phase angle. Flight controllers for power convertors can be one of two general forms. One is a passive, analog circuit that provides some equivalent net electric resistance to the terminals of the alternator to maintain piston amplitude at the desired level, based on some control requirement such as power, voltage, or heater temperature. The other is a digital circuit that actively controls the flow of current to maintain piston amplitude. The former type requires tuning capacitors while the latter type does not. In general, the latter type of controller uses power electronics to create the AC current waveform that acts as a load to the power convertor, as does the power supply for the cryocooler that creates the AC drive power from the DC power source.

One of the biggest differences between a Stirling cryocooler and a power convertor is in the physical size and structure of the cold finger and the heater head. As mentioned previously, cryocoolers are generally designed to lift approximately one to 10 W of heat from a very low temperature, and reject it through some thermal management system. This can take 10s to 100s of watts power input to drive the linear motor. Stirling power convertors that are designed to produce 100 W power output will be driven by 200 to 250 W of heat input. The heat flow through the heat exchangers is fundamentally different for a similar physical size of machine, and an electrically similar size of machine. In both cases, the design is optimized to minimize the thermal conduction along the heater head of the power convertor, and the cold finger of the cryocooler. The difference is that an optimized Stirling power convertor will have a much larger diameter, and thicker wall heater head than an optimized cold finger of a cryocooler. This provides a much more rugged and robust heater head, which is generally not a structural challenge for the designers to achieve, rather it is inherent in the design. This is illustrated in figure 18, which shows a prototype of the ASC power convertor by Sunpower with a linear alternator rated at approximately 100 W and a cryocooler by Sunpower, with a linear motor rated at about 150 W. Both units use the same

a) power convertor b) cooler

Figure 18.—Power convertor on left compared to cooler on right. *ASC on left showing proportion of heater head diameter to linear alternator, and cooler on right comparing cold finger diameter to linear motor.*

technology for the alternator and the motor, thus the visual difference in the diameter of the Stirling heater head compared to the cold finger can be attributed to thermal optimization and the difference in the heat flows.

Another fundamental difference is the time at which the cryocooler operates compared to the power convertor. Cryocoolers are commonly not operating during launch and the moving components will sometimes be locked in place to be stationary. Following a successful launch, operation of the cryocooler will be started as the spacecraft is checked out and the instrument begins operation in the mission. The only known operation of a Stirling cooler during launch was on Space Shuttle Discovery on STS-60 in 1994, in which a Stirling cooler was used in a refrigerator for the astronauts. A radioisotope power system will be operated from the time when the plutonium fuel is loaded into the generator in the GPHS module. Shortly after heat is applied to the heater head, operation must begin so that heat can be removed from the module and prevent over-temperature. Operation of the Stirling convertors will continue during transport to the launch site, storage, installation on the spacecraft, and during launch. While this was a major concern in 1999, and had not been researched through test, many tests have been conducted that indicate that operation during launch is manageable. To date, a complete Stirling generator has not been tested, however, individual convertors have been tested to high levels, and generator simulators have been characterized to determine the transmissibility. A combination of the test results of the generator simulator, and of TDC no. 1 indicate that launch vibration up to 12.3 g (0.2 g^2/Hz) is tolerable, with projections of surviving at levels up to 15.1 g (0.3g^2/Hz). The EE-35, shown in figure 19 mounted in vibration test configuration at the GRC Structural Dynamics Laboratory, survived a 3-min test at nearly 24 g (0.8 g^2/Hz), while another unit survived the same level in the lateral direction.

Aside from the technical similarities and differences between cryocoolers and long-life, non-contacting power convertors, they share a common programmatic challenge. In neither case is there a way to conduct accelerated life testing of a complete unit or system. The problem arises from the fact that life-limiting mechanisms have been eliminated by design in both cases. In the power convertor, one could argue that the heater head will creep due to the elevated temperature and the internal pressure, however with reduction in temperature the creep process becomes negligible. Creep analysis of a heater head has been refined and it is now dealt with on a probabilistic basis so the risk of performance being affected can be managed in the design process, and a heater head can result with any value of reliability necessary. Individual components are often subjected to accelerated life test including magnets for the alternator, flexures, and heater heads. Since these components have their lives accelerated by fundamentally different mechanisms, stress or pressure for the heater head, stress or amplitude for the flexure, and magnetic stress or temperature for the magnet, it is not possible to accelerate the life of the integrated unit.

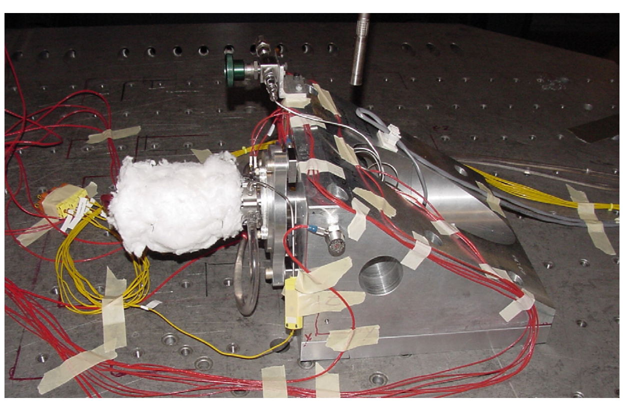


Figure 19.—EE-35 Vibration Test. *An EE-35 mounted on the shaker table at GRC in preparation for vibration test. The convertor operated successfully up to nearly 24 g.*

What remains is a challenge of verifying long life of the integrated Stirling device that has no wear-out mechanisms to be accelerated (ref. 35). A very general approach has evolved in the cryocooler community, whereby a cryocooler is considered for long-life application when it has met three criteria; it has 1) been designed with accepted long-life technologies eliminating all wear mechanisms by design, 2) gone through thorough design reviews by highly qualified personnel, and 3) demonstrated operation of approximately 1 year with no degradation. A methodology such as this will be necessary for Stirling power convertor designs for radioisotope systems of the future since it appears that a system level accelerated life test is not possible.

An example of the state-of-the-art in long-life Stirling cryocoolers can be taken from the experience of Superconductor Technologies Incorporated (STI), of Santa Barbara, California. The company produces filters for the telecommunication industry based on high-temperature superconductivity. Their filters operate at low temperatures and use a long-life Stirling cryocooler to cool each filter. The STI cryocooler technology has many similar features to that found in the ASC. While there is no requirement to survive launch vibration, the coolers do operate at ambient temperatures ranging from –40 to +60 °C atop the cell phone towers. STI developed their cooler through a licensing agreement with Sunpower, and the initial units were deployed in 1997. In 2004, it was reported that there were over 4,000 coolers in the field, with a manufacturing cost of <$3,000 each, with a Mean Time Between Failure (MTBF) of >500,000 hr for all of the coolers, based on operating data from the field and in-house test results. The coolers had accumulated over 44,000,000 hr of operation (refs. 36 and 37). Of these, 460 coolers have more than 26,280 hr each. A Pareto analysis of the cooler was used in 2002 to identify potential design and reliability improvements. Since that time, more than 2,600 units have been put into service, accumulating over 15,000,000 hr, and only three have failed; not one was related to wear. The data shows no infant mortality and no indication or wear out, therefore the failure rate is constant. With the data collected, the MTBF of the units produced since 2002 can be calculated as >1 million hr. The dilemma is that the data indicates very high reliability, yet there are too few failures to determine a statistically significant MTBF. This example shows that a highly reliable Stirling cooler can be produced, in a cost-competitive market, if properly developed and produced under an adequate QA process.

As Stirling cooler and power convertor designs mature, and long life has been demonstrated, failures due to design flaws are eliminated. Failures may still occur, however, they will be the result of a probabilistic set of events, and may require a particular combination of several events to trigger the failure. When a design has been reached this state of development, and fundamental design flaws no longer exist, the failures experienced among a population of units will be more random in nature, and it will be less likely to have multiple failures at a given time. That is to say, common mode failure should not exist. Realizing this state of development can influence the use of redundancy as a method of enhancing reliability in a system.

Lastly, after decades of development, it appears that free-piston Stirling power convertors are nearing commercialization. Teams are developing commercial cogeneration and microgeneration units for domestic use in Japan and in Europe (refs. 22 and 38). These units will be hermetically sealed, long-life convertors based on the principles of non-contacting operation. Similar to the commercial cryocoolers, they will need to be cost competitive, and thus will rely on a matured design with long life ensured through controlled manufacturing under a QA process. Field trials have been completed and facilities are being prepared for production. As a significant number of these units are put into application, they will provide more data regarding the ability to achieve long life and high reliability in Stirling convertors. Smaller units are being developed for military applications, at 35 W for soldier-carried portable power, or at 160 W as battery chargers (ref. 39). The military applications have some of the same requirements as NASA applications in terms of low mass and uncompromised reliability.

B. Advanced Technology

Advances have been made in the pursuit of improved performance. The most common metric considered for convertors for space power applications is the specific power of the fully integrated system. The TDC that was used in the SRG110 design had specific power of the Stirling convertor of about 15 W per kg. Through SBIR's, and an advanced technology effort at GRC, many of the technologies necessary for significant increase in specific power were developed (ref. 40). The first example of the increase in specific power was shown in the EE-35 developed by Sunpower (ref. 41). 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 achieved similar levels of specific power. High levels of specific power were projected to be possible in the past, however, development of the EE-35 and the ASC have demonstrated this in hardware. With the higher specific power of the Stirling convertor, it appears that a radioisotope generator could achieve approximately 8 W per kg, potentially enabling radioisotope electric propulsion missions (ref. 42). Further advances may be achievable through the use of ceramics or refractory alloys, but it would bring some amount of developmental risk.

Higher specific power of the Stirling convertor does not appear to have compromised the ruggedness of the design. 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 g^2/Hz) random vibration. The EE-35 was tested at GRC in 2004 and survived nearly 24 g (0.8 g^2/Hz) vibration. The only failures noted were breakage of a fill tube that would not be attached in a space mission, and failure of a controller, once again, of the type that would not be used in a space mission. 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 g (0.3 g^2/Hz) input to the generator (ref. 43).

Another area where advanced technology is providing a benefit is in the controller. Previous controllers used tuning capacitors between the linear alternator and the controller to compensate for the inherent inductance of the coil of the linear alternator. Compensation of the inductance would flow current through the linear alternator in phase with the velocity and the electromotive force generated, thereby minimizing reactive current and the associated resistive losses. A relatively new technique to minimize reactive current without the need for tuning capacitors is with 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 were found to 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. 44), 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.

C. Findings of Relevant Studies

Dynamic cryocoolers is space applications are relatively rare since there have only been 32 cryocoolers that have been put into space, of which 31 were Stirling cryocoolers. Dynamic power conversion in space has not yet been attempted. A number of studies have been conducted to investigate the benefits and challenges in developing and deploying a dynamic power system. Findings from the studies are somewhat similar. The 1997 study concluded that Stirling power conversion technology was generally available, and that the major effort in the future needed to be in system integration (ref. 18). Similarly, the 1999 Technology Readiness Assessment found that the technology was sufficiently mature to allow flight development to proceed (ref. 23). The major effort remaining as flight development was initiated was system integration. It should be pointed out, that following development of the power conversion technology, system integration is not a simple task. System integration of a power conversion technology, for a long life, high reliability, deep space radioisotope power system is an inherently complex task. Thus, recommending that the power conversion technology is sufficiently mature to enter into system integration is not a suggestion that system integration will be straightforward. Other studies resulted in similar conclusions recommending that Stirling should be pursued as the primary focus to develop a high-efficiency, long-life power system, to be available for future space power applications, and that other power conversion technologies that are less risky, should continue to be pursued as a backup option to Stirling.

V. Current State of Development

A summary of the state of development of free-piston Stirling power conversion, as it applies to a radioisotope space power system will now be provided. Stirling power convertor designs exist that are applicable to space power. They are not conceptual designs as existed in the past; rather, as in the case of the TDC, they are detailed designs that are very well characterized. Similarly, detailed generator designs exist that are fully applicable to space power and are not 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 EU generator. The original specification did not require the generator to be fully autonomous, but could rely on parasitic load resistors on a spacecraft to dump excess power not being consumed by the end user. In other words, the spacecraft would provide a constant load to the generator, taking all of the power generated by the Stirling convertors. As the design evolved, the requirements were amended to require the generator to be able to operate autonomously, supplying anywhere from zero power to full power to the end user and dissipating any power generated that was not used by the end user. 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 to 90 W/kg. 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 characterize fully 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, which began developing power convertors in the early-1970s as nautical navigational aids such as in buoys and lighthouses. Designs of the Thermo-mechanical Generators (TMG) were developed in the range of 25 to 65 W power output, and were heater electrically in the lab, or by propane or isotope fuel. The key feature of the design that enabled long-life was non-contacting operation, achieved by using diaphragms to support the moving components (ref. 45). 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; however, the ability to operate a dynamic system with long life was demonstrated. Other sources of data are becoming available with over 80,000 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 convertors has been demonstrated. While this should not present a significant challenge, it remained unproven until recently. Hermetic sealed convertors were developed and demonstrated by Infinia under the SRG110 project, and ASC convertors are being prepared for hermetic sealing by Sunpower.

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 life. The analysis provides life in a probabilistic sense, and tests to validate the analysis were initiated at GRC. There have also been some limited efforts to investigate the use of organics to ensure long life. Both of these are rather application specific, however, neither the metallics nor the organics appears to present a problem. 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 survive at levels nearing the limits of the heat source. 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. 46). 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 1 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. This includes the heat source, through 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. 47). The 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, which is the standard of the industry, to use a more accurate thermodynamic model. SDM has started to be used in a production mode at GRC to support controller development and high-power system studies at GRC and at LM. SDM has also been used to analyze operating points of complex systems, to look at transient response, and to analytically determine gains for controllers prior to testing.

Perhaps the greatest area of advancement in free-piston Stirling power convertors over the past decade is in the area of system integration. This is particularly true for radioisotope space power since the inception of the SRG110 project. As mentioned previously, system integration is being performed for space power applications and for terrestrial applications, both commercial and military. For space power, prior projects did not address as many aspects as of system integration as have been included in the SRG110. 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. However, even considering the great progress that has been made, there are still some lessons that remain to be learned.

VI. 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 with rotary alternators to convert heat to electricity. These systems were proposed with lightly loaded linkages to achieve the necessary life. 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. These features have consistently been recognized by teams that have studied technology options for radioisotope 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: demonstration of life and reliability, the success achieved by Stirling cryocoolers in flight, and the overall developmental maturity of the technology for both flight and terrestrial applications. Based on these advances, free-piston Stirling convertors are currently being developed 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, and discuss the challenges that remain.

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