



# Summary of Stirling Convertor Testing at NASA Glenn Research Center

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This report contains preliminary findings, subject to revision as analysis proceeds.

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# Summary of Stirling Converter Testing at NASA Glenn Research Center

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## Abstract

The NASA Glenn Research Center (GRC) has been testing free-piston Stirling converters for potential use in radioisotope power systems. These converters tend to be in the 35 to 80 W electric power output range. Tests at GRC have accumulated over 80,000 hr of operation. Test articles have been received from Infinia Corporation of Kennewick, Washington and from Sunpower of Athens, Ohio. Infinia designed and built the developmental Stirling Technology Demonstration Convertors (TDC) in addition to the more advanced Test Bed and Engineering Unit convertors. GRC has eight of the TDC's under test including two that operate in a thermal vacuum environment. Sunpower designed and developed the EE-35 and the Advanced Stirling Converter (ASC). GRC has six of the EE-35's and is preparing for testing multiple ASC's. Free-piston Stirling converters for radioisotope power systems make use of non-contacting operation that eliminates wear and is suited for long-term operation. Space missions with radioisotope power systems are often considered that extend from three to 14 years. One of the key capabilities of the GRC test facility is the ability to support continuous, unattended operation. Hardware, software, and procedures for preparing the test articles were developed to support these tests. These included the processing of the converters for minimizing the contaminants in the working fluid, developing a helium charging system for filling and for gas sample analysis, and the development of new control software and a high-speed protection circuit to insure safe, round-the-clock operation. Performance data of Stirling converters over time is required to demonstrate that a radioisotope power system is capable of providing reliable power for multi-year missions. This paper will discuss the status of Stirling converter testing at GRC.

## Nomenclature

|        |  |
|--------|--|
| ASC    | advanced Stirling converter              |
| ASRG   | advanced Stirling radioisotope generator |
| DOE    | Department of Energy                     |
| EWI    | Edison Welding Institute                 |
| FPC    | failsafe protection circuit              |
| GPHS   | general purpose heat source              |
| GRC    | Glenn Research Center                    |
| LM     | Lockheed Martin                          |
| RGA    | residual gas analyzer                    |
| SBIR   | Small Business Innovative Research       |
| SRG110 | 110 W Stirling radioisotope generator    |
| TDC    | technology demonstration converter       |

## I. Introduction

The NASA Glenn Research Center (GRC) has been involved in the development of high-efficiency Stirling power conversion technology since the 1970's. During some of this time, there was an advanced technology effort in parallel with applied research or development efforts. The advanced technology efforts were generally limited in scope and focused on basics of fluid flow and heat exchangers, advanced component technologies, and development of Stirling converters with increased temperature capability, enhanced reliability, increased efficiency and/or reduced mass compared to the state-of-the-art. The development efforts focused on system integration issues and providing data necessary to ensure long life and high reliability in the system context. Examples of development projects that were intended for potential space flight include the SP-100 and the 110-W Stirling Radioisotope Generator (SRG110) projects. One source for the data used to support these projects is testing of Stirling converters.

These can be either focused tests that are relatively short term and used to investigate specific questions about the operation, or they can be extended operation tests to examine operating trends over long periods. The extended operation tests are of particular interest for radioisotope power applications since the missions where Stirling power conversion is often considered are generally long duration missions and can have a life requirement of up to 15 years or more. The term extended operation was chosen to describe these tests since they were meant to identify any changes in operation that might be attributable to operating for long periods of time, rather than an endurance test that is meant to find the endurance limit and ultimately fail a device.

Development of the SRG110 was undertaken by the Department of Energy (DOE) to provide NASA with a multi-mission 100-W class radioisotope generator (ref. 1). DOE selected Lockheed Martin (LM) of Valley Forge, Pennsylvania as the system integration contractor teamed with Infinia Corporation (formerly Stirling Technology Company) of Kennewick, Washington as the supplier of Stirling convertors. GRC was a member of the SRG110 team supplying Stirling related expertise, supporting technology through the GRC matrix system, and providing the capability for a range of tests involving Stirling convertors and components. The SRG110 generator was projected to be greater than 20 percent efficiency, with a beginning of mission power output of 116 W and a mass of 33 kg for a specific power of 3.6 W/kg. Infinia designed and built 16 Stirling Technology Demonstration Convertors (TDC's) under the direction of DOE prior to LM being selected as the system integration contractor. The TDC was designed to use the nominal 250 W of heat from one General Purpose Heat Source (GPHS) module and realizes non-contacting operation of the moving components through a flexure based bearing system to achieve long life. At the request of LM, part of the GRC Stirling convertor test effort included Extended Operation of TDC's in the dynamically balanced, dual-opposed configuration. Initially, TDC's #13 and #14 were put on test (ref. 2), followed by TDC's #15 and #16. GRC also initiated an extended operation test with TDC's #5 and #6 in a thermal vacuum facility to simulate operation in deep space. In addition to the Extended Operation Tests, other tests have been performed that are short-term, intended to investigate particular aspects of performance such as start-up transient, imbalanced operation, and transient response. Many lessons have been learned through the extensive testing and the capability of the test stands has been improved.

Under a NASA Small Business Innovative Research (SBIR) contract, Sunpower of Athens, Ohio developed the EE-35 convertor. This convertor was sized for the heat provided by one-half of a GPHS module. Due to flight development of the SRG110 generator, extended operation testing of the EE-35's has been lower priority than testing of the TDC's and much less time has been accumulated. More recently, Sunpower developed the Advanced Stirling Convertor (ASC) under a NASA Research Announcement contract. The ASC The Sunpower convertors use a system of gas bearings to eliminate wear and achieve non-contacting operation for long life. Preparations are currently underway for extended operation testing of ASC's to begin later in 2006.

## **II. Description of the Extended Operation Test System**

Free-piston Stirling convertors have been operated at GRC since the late 1970's for a diverse set of applications including residential heat pumps, terrestrial power generation, nuclear space power, and radioisotope space power. All of the hardware discussed in this report was developed to support radioisotope space power applications. The standard heat source for this application is the GPHS module, which nominally provides 250 W of heat at the beginning of life, or about 227 W net heat input to the Stirling convertor after system level insulation losses. The heat is reduced over time as the isotope decays with an approximate 78-year half-life. Stirling convertors developed for radioisotope power, such as the TDC and the ASC, are typically designed to receive up to 250 W of heat and convert the heat to electricity with high efficiency. Some designs, such as the EE-35, have been proposed that would use one-half the heat of a GPHS module, thereby needing two Stirling convertors per GPHS module (ref. 3), and others for the heat provided by two GPHS modules. The thermoacoustic Stirling built by Northrop Grumman and Los Alamos National Laboratory under the High Efficiency Power Source project is an example of the latter (ref. 4).

TDC's #5 and #6 were received by GRC in September of 2000. They were early developmental convertors for the radioisotope application. Since being received at GRC, they have been used for a wide range of tests including performance characterization and a variety of controller tests. All of these tests were relatively short-term, focused tests that were conducted in the presence of a test engineer. TDC's #7 and #8 were delivered to GRC in March of 2001 and were similarly used for a range of short-term, focused tests. Following selection of LM as the SRG110 system integration contractor, TDC's #13 and #14 were sent to GRC for an Extended Operation Test. These TDC's were the first convertors built by Infinia under the Quality Assurance Program that was being developed in preparation for the eventual fabrication of flight hardware. TDC's #13 and #14 were put into Extended Operation testing in June of 2003. The Extended Operation Test was originally conceived to be a 5,000-hr test; however, a programmatic decision was made to continue the test believing that there was greater value in accumulating more

hours of operation rather than terminating the test and risking damage to the hardware in a subsequent inspection. Continuous operation was needed to be able to meet the original test requirement of 5,000 hr (approximately 208 days continuous days) in a reasonable period. To achieve continuous, reliable operation of the test, development was required of test stand hardware, data system and control software, and procedures for the preparation of the Stirling convertors.

#### A. Test Station

The test station includes a rack with the data system and controls, the test stand or table, the cooling system, and the gas management system. A pair of TDC's, in the dual-opposed configuration is shown on a test station at GRC in figure 1 and in more detail in figure 2. The data system is based on LabVIEW (National Instruments) commercial hardware and software, and is used to monitor operation and record data. The software was developed for unattended operation to include automatic shutdown of the convertors in the event of a failure or detection of an out-of-range reading in the operating condition. Some of the conditions that are monitored by the data system to initiate a shutdown include the hot-end temperature, cold-end temperature, pressure vessel temperature, convertor pressure, piston stroke, coolant flow, and utility power. When an out-of-range condition is sensed, the LabVIEW data system initiates shutdown of the system. If a loss of utility power is sensed, the test stand can be operated by an



Figure 1.—A pair of TDC's mounted on a test stand at GRC under Extended Operation Test.

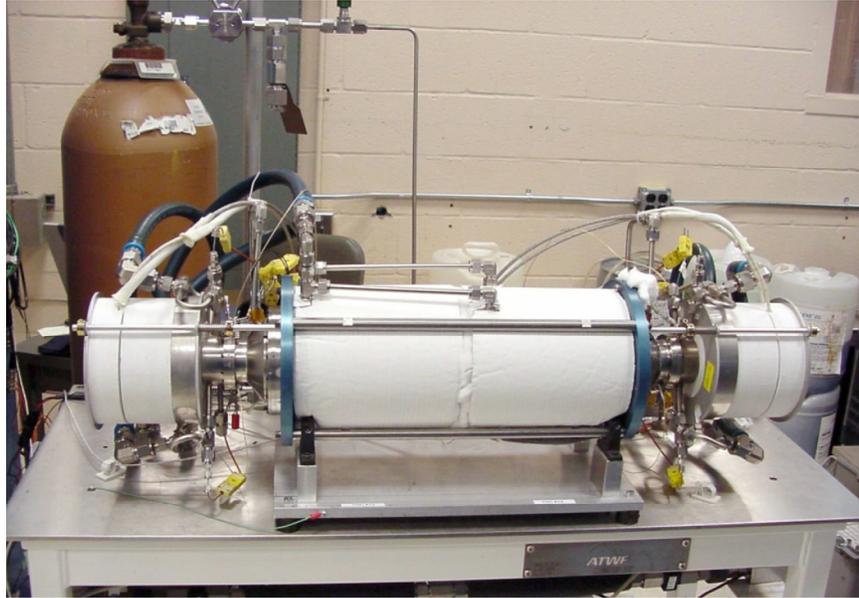


Figure 2.—Dual-opposed TDC's on a test stand with insulation around the heater heads and the pressure vessels.

Uninterruptible Power Supply for 5 min before a controlled shutdown is initiated. In the event of a software initiated shutdown, LabVIEW sends commands to turn off the heater power supplies, set the circulator temperature set points to 20 °C, and generates a freeze file of all monitored parameters covering a time period of 10 min prior to the shutdown and 5 min afterward. Two types of shutdown were developed: one for an emergency shutdown that stops the converters as quickly as possible, and the other providing a slower, more controlled shutdown.

Additional safety is provided by hard-wired shutdowns that were designed into the data system racks and do not rely on the LabVIEW software. Such steady state parameters include over temperature of a specified hot-end thermocouple that can initiate shutdown via a meter relay, and loss of coolant flow can initiate a shutdown via a flow switch. In both cases, the shut down will turn off the power supplies for the electric heaters. The Failsafe Protection Circuit (FPC) is an electronic circuit that was developed to monitor up to five dynamic signals and initiate a shutdown if any parameter is sensed as being out-of-range. The FPC was designed to react in less than one-half cycle of operation of the converters. The FPC is typically used to monitor piston position transducers or accelerometers mounted on the convertor assembly. It responds by sending a signal to the LabVIEW data system to initiate shutdown, while at the same time putting a fixed resistive load directly on the output terminals of the linear alternators to keep the piston amplitudes at a safe level.

During normal operation, the data system measures, displays and records operational parameters including temperatures, voltage, current and charge pressure of each convertor. Data can be acquired and saved to the hard drive of the data system computer in three ways, including a five-minute average, a continuous set of data that can be recorded at a user-defined rate of up to 30 scans per minute, and a user-initiated freeze file.

Two cooling loops are used at each test station, one to remove waste heat from the cold end of the Stirling cycle and the other to control the temperature of the pressure vessel and linear alternator of the Stirling convertor. These two temperatures will be different in most radioisotope generators and need to be controlled to represent operation in an integrated generator and enable accurate measurement of the performance. Ethylene glycol coolant has been used in both of the circulators and heat exchangers.

When operated as a dual-opposed pair, the converters are typically mounted rigidly to an aluminum base plate that is attached to the steel test stand with rubber isolation mounts. When operation is dynamically balanced, there is no net vibratory force generated, and the compliance and/or damping of the rubber isolation mounts have no bearing on the dynamics of operation. When the operation is knowingly forced to be in an unbalanced condition, the compliance of the mounts are characterized or customized as necessary for the test.

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

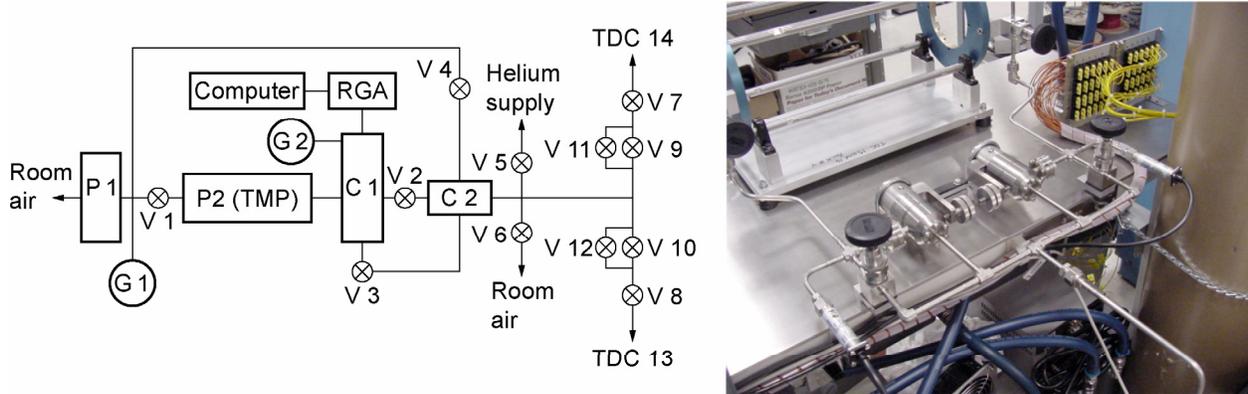


Figure 3.—Gas charging system. Schematic of gas charging system manifold along with photograph of manifold on a test stand. The turbomolecular pump and the RGA are located below the manifold.

measure any changes that may occur over time. It was speculated that there could be some outgassing from the organics in the linear alternator. While small amounts of non-helium working fluid do not result in a measurable impact on thermodynamic performance, there is a concern that impurities in the working fluid may potentially react with other internal components, such as the regenerator. The damaged components may adversely affect convertor performance or life. A schematic and a photograph of the gas charging system are shown in figure 3. The principal components of the system are the turbomolecular vacuum pump, the quadrupole RGA, and the manifold with isolation and leak valves. The manifold shown in the photograph was fabricated from stainless steel tubing with orbital weld joints wherever possible to eliminate potential leakage and/or contamination. Relief valves were eliminated in favor of burst disks to minimize the chance of leakage.

### III. Results of Operation

Extended operation tests have been conducted primarily with TDC's, with some limited operation of the EE-35's. Preparation is underway for testing the ASC's. While the operation of all of the convertors is similar, there are slight differences in the voltage of the electric heaters, the output voltages from the linear alternators, and the physical dimensions that requires modifications to the test station. A summary will be provided of the experience with the TDC's, the EE-35's, and the ASC's.

#### A. Operation of the TDC's #13 and #14

TDC's #13 and #14 were received at GRC in February of 2002 for an extended operation test. The TDC's were installed on the test stand in preparation for bake out. The primary purpose of the bake out was to remove any moisture or other sources of oxygen that would allow the stainless steel regenerator to oxidize at the operating temperature. Bake out began on March 19, 2003. The convertors were maintained at approximately 80 °C while the turbomolecular vacuum pump evacuated the internal volume. The bake out lasted approximately 500 hr with the results summarized in figure 4. The total pressure was measured at  $4 \times 10^{-6}$  torr, with about  $1 \times 10^{-6}$  torr of water. A small amount of isopropyl alcohol was also detected by the RGA, which was believed to originate from the cleaning during manufacturing.

The convertors were first operated in April 2002. Short tests were performed to check out performance of the convertors and operation of the test station, with full-power operation established in June 2002. The test station and the convertors were deemed ready for extended operation by June 2002. During the early stages of extended operation, some of the electric connections of the electric resistance heaters failed. These TDC's use ten electric resistance heaters evenly spaced around a nickel ring attached to the external surface of the heater head. They simulate the heat that would be supplied by a GPHS module. The decision was made to replace the wiring of the heaters in July 2003. Nearly continuous operation resumed in August, and 1,317 hr of operation was accumulated by the end of the month.

Early in testing, it was noted that there was a loss of about 3 psi of helium per week from the nominal fill pressure of 365 psig. It was not known if this was permeation through the o-ring seals of the bolted flanges of the TDC's or if it was leakage from a fitting. The fittings were inspected and no leakage could be detected. By the beginning of October 2003, it was apparent that the efficiency had decreased slightly, from about 27.2 to 27.1 percent on TDC #13 and from about 26.7 to 26.5 percent on TDC #14. At the same time, it was noted that the

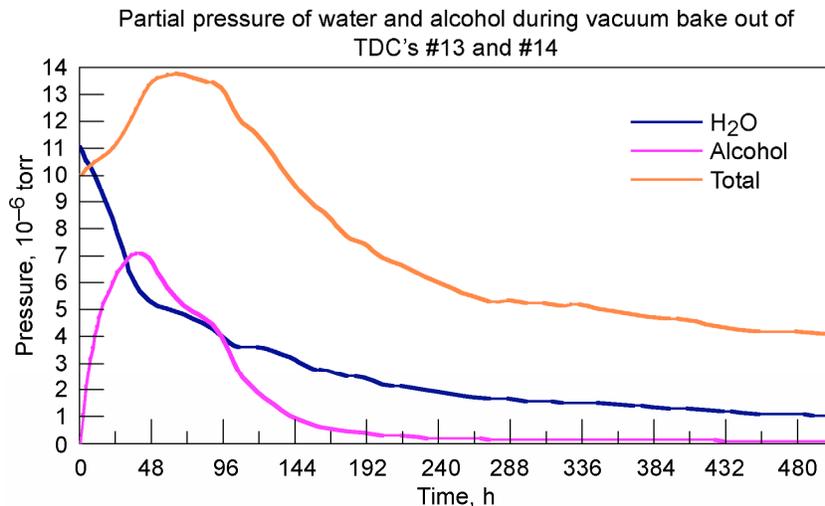


Figure 4.—Gas analysis results from bake out of TDC,s #13 and #14.

gas analysis of the working fluid was showing increased concentrations of argon and nitrogen. It was hypothesized that helium was permeating outward through the o-rings and that ambient atmosphere was permeating inward. The source of argon was believed to be pockets formed by blind holes with fasteners inserted with Loctite (Loctite Corporation), the pocket being filled with argon during insulation loss tests. The source of nitrogen was believed to be the ambient atmosphere with the oxygen being consumed by oxidation of the stainless steel regenerator, and thus no oxygen appearing in the gas analysis. The consumption of oxygen by the regenerator was also hypothesized to be the reason for the slight decrease in operation efficiency.

The TDC's were shut down to conduct a test to investigate the permeation. The convertors were motored with the hot end and the cold end of the TDC's at nominal 80 °C. This resulted in the o-rings being at the same temperature as during normal operation, which should have resulted in permeation of helium outward and ambient atmosphere inward. With the reduced hot-end temperature, the oxygen would not be consumed by oxidation and should have been detected by the RGA. However, the test did not showing the expected result of permeation of helium outward, nor nitrogen and oxygen inward. With the inconclusive results, the extended operation test continued with plans made for installing purge rings around the bolted flanges that would provide a controlled inert atmosphere outside the o-rings. Purge rings were installed following 2,800 hr of operation with argon used to cover the o-ring flanges. The choice of argon was based on the original goal of 5,000 hr of operation and calculations that showed that the concentration of argon that would result from this amount of operation would not affect the thermodynamic performance to a measurable extent. The results were immediate, with the concentration of nitrogen remaining constant and the concentration of argon increasing. This result was consistent with the hypothesis that the gasses were permeating through the o-ring during operation and that the oxygen was being consumed by the regenerator.

As stated earlier, the test was originally intended to be a 5,000-hr test; however, the decision was made to continue operation beyond 5,000 hr rather than terminating the test for an invasive inspection. Since this could possibly result in concentration of argon that would have a measurable influence on the thermodynamic performance, the decision was made to change the purge from argon to helium resulting in a helium atmosphere both inside and outside the o-rings. The change to helium purge was made after 6,500 hr of operation with the result that the argon and the nitrogen concentrations stayed constant, and even decreased slightly over time. As operation continued with permeation of oxygen into the convertor eliminated, the performance became level with no change in conversion efficiency, even though it is believed that the regenerator suffered damage during the early operation.

TDC's #13 and #14 were shut down in August 2004 to be moved to a new test facility. It was often found during this test that slight changes in performance were due to the ability of the facility to maintain constant operating conditions. Slight changes in the operating conditions resulted following the move, caused by the transient on the external support systems, and not changes in the convertors. While the TDC's appeared healthy following the move, slight changes in the insulation and some modifications to the coolant flow lines resulted in a change to the operating point.

The coolant composition was changed from ethylene glycol to a 50/50 mixture with water after 12,000 hr. This resulted in unacceptable daily changes in coolant composition, as water would evaporate from the system causing an

increased concentration of ethylene glycol in the mixture. At 12,500 hr, the composition was allowed to change slowly back to pure ethylene glycol by replacing the evaporated water each day with ethylene glycol until all water was removed.

Operation continued until about 19,000 hr; at which time TDC's #13 and #14 were scheduled for shutdown for hermetic seal welding of the bolted flanges. Prior to this shutdown, the TDC's were vented and filled with a clean supply of helium. The purpose of this was to try to quantify any measurable change in performance due to the small concentration of argon and nitrogen in the working fluid. The impact in performance was not detectable. Temperature was reduced, and data were recorded at a low-temperature operating point for future reference. The low-temperature operating point was selected with the hot end at 500 °C so that oxidation of the regenerator would be minimal with some oxygen remaining in the working fluid. When at this reduced hot-end temperature, the cold-end temperature was also reduced to maintain the design temperature ratio and thus full power. The design of these bolted flanges was such that, even after hermetic seal welding, bolts were required to provide structure and spacers were required to minimize flange rotation and the resulting stress. The spacers that were installed in TDC's #13 and #14 prior to the weld were continuous rings that required the heater heads and the pressure vessels to be removed prior to welding. The heater heads and the pressure vessels were removed, the spacer rings were removed, and the heater heads and pressure vessels were reinstalled for welding. At the same time, the spacer rings were split into two half-circle segments to they could be installed after welding.

When the heater heads and the pressure vessels were removed, a noninvasive inspection was performed. The inspection was visual with very limited ability to take samples. The inspection was conducted by a team from GRC and Infinia after 19,000 hr of operation. The inspection was looking specifically for indications of wear on surfaces, particles that may have resulted in wear, debris from the regenerator, accumulation of particles on the magnets of the linear alternator, and visual evidence of aging of the organics in the linear alternator. The inspection found no evidence of wear during operation or debris. Slight markings that were observed were generally attributed to the original build process. The TDC's were operated for a short period following inspection to verify that the inspection did not alter the operation in any way.

Hermetic laser seal welding was completed by the Edison Welding Institute (EWI) of Columbus, Ohio in January 2007. The TDC's were tested for a short period at the low-temperature operating point following the welding process to verify proper performance. Operation was nominal and generally in agreement with the pre-weld operation at the low-temperature operating point; within the ability to control the operating point and to read the data. The TDC's were then shut down for bake out to allow for a high purity fill with helium. This bake out lasted only 125 hr and resulted in a total pressure of  $4.5 \times 10^{-7}$  torr, with the dominant species being water.

TDC's #13 and #14 were then returned to full-power operation. However, at 20,600 hr, one of the ten electric resistance heaters failed on TDC #13. Operation is continuing with ten heaters working on TDC #14 and only nine working on TDC #13. The operating points have been adjusted so that the two TDC's have equal average hot-end temperature and equal net heat input. TDC's #13 and #14 recently surpassed 21,000 hr of operation with no failures or otherwise anomalous operation that could be attributed to the TDC's.

Test data from TDC's #13 and #14 are shown in figure 5. The slight degradation in conversion efficiency can be seen through the first 5,000 hr of operation. The transient in performance around 8,000 hr is a result of the move to the new test facility causing some disturbance to the insulation and changes in the coolant flow rate due to

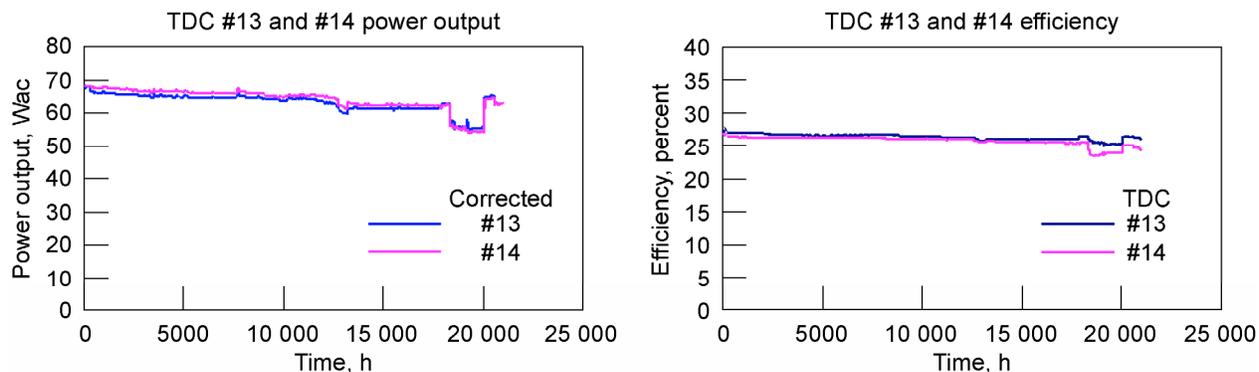


Figure 5.—Performance data from TDC's #13 and #14 through 21 000 hours of operation.

modifications in the cold-end plumbing. The change in performance at 12,000 hr was due to the change in coolant composition. After the ethylene glycol was diluted with water and then returned to pure ethylene glycol, it was found that some of the additives included in the coolant by the manufacturer were crystallizing and affecting the coolant flow rate and flow patterns in the heat exchangers. The transient at about 18,600 hr was in preparation for hermetic seal welding, with a return to full operating conditions at about 20,000 hr. Changes noted at 20,600 hr are due to the one failed heater on TDC #13 and the subsequent adjustment in the heater temperatures. Operation will continue with one failed heater, however, the TDC's may be shutdown and the heaters replaced if one more heater fails and balanced operation is no longer possible.

### **B. Operation of TDC's #5 and #6**

TDC's #5 and #6 were early developmental convertors built prior to the Quality Assurance Program used on TDC's #13 and #14. Since being received at GRC they have been used for a wide range of tests including performance characterization and a variety of controller tests. All of these tests were relatively short-term, focused tests that were conducted in the presence of a test engineer. A decision was made to put TDC's #5 and #6 into extended operation in a thermal vacuum environment that would simulate operation in deep space. Heat would be supplied to the heater head from electric heaters through a heat collector, waste heat rejected by a cold flange and radiator panels, and the operating temperatures would be determined by conduction and radiation paths inherent in the hardware. While the test configuration would be somewhat representative of the SRG110, there was no consideration to the mass of the test article. This test required some of the components of the TDC's to be replaced or modified.

The test article as installed in the vacuum facility at GRC is shown in figure 6. Heater heads were fabricated with prototypical heat collectors similar to those that would be used to transport heat from a GPHS module to the Stirling convertor in the SRG110. Borelectric (GE Advanced Ceramics) heaters were clamped to the heat collectors to simulate the GPHS modules. The heat collectors were instrumented with thermocouples to characterize the temperature distribution during operation. One of the purposes of the thermal vacuum operation was to validate analysis of temperature profiles when the conduction-driven heat collector was integrated with the Stirling cycle heat exchanger of the heater head. The heater head was fabricated with a nickel flange brazed to the heat rejection area to conduct waste heat to the radiator panels. The nickel flanges were sandwiched between copper plates to enhance net conductivity. Two sets of radiator panels were made to allow adjustment of the cold-end temperature during operation. The GRC-developed transverse Hall Effect position sensors were installed to measure piston position. These sensors required electric feed throughs for the position signals, thus rings were designed and fabricated with wire feed throughs that were installed into the bolted flange between the piston housings and the

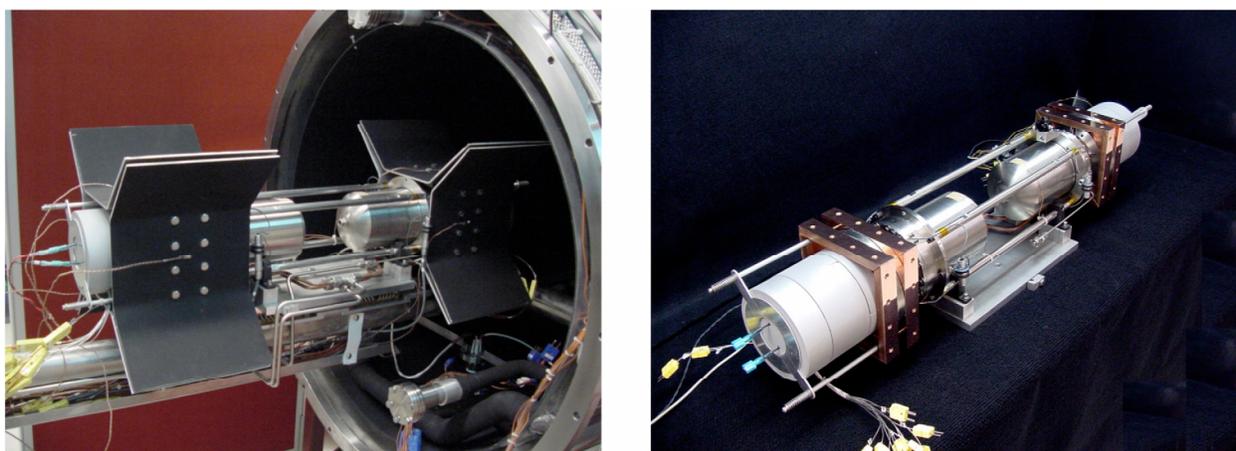


Figure 6.—TDC #5 and #6 configured for thermal vacuum extended operation test.

pressure vessels. This resulted in an assembly with three o-rings to contain the helium working fluid. It was known that there would be some permeation of helium into the vacuum facility, requiring the pressure to be topped-off occasionally; however, it was also known that there would be no oxygen in the surrounding atmosphere to permeate inward.

TDC's #5 and #6 were initially operated in the thermal vacuum facility in November 2004. After nearly 1,000 hr of operation at approximately 500 °C, the temperature was increased to slightly more than 600 °C. A fastener used to connect the electric lead to one of the Borelectric heaters failed within 100 hr of increasing the temperature. It was found that the molybdenum fasteners used for the electric connection to the silicon carbide heater were yielding at the operating temperature. When the test article was returned to ambient temperature due to a vacuum facility related issue, the fastener lost preload, leaving the electric connection loose. The molybdenum fasteners were replaced with fasteners made from A286. This improved the operation, however these fasteners were found to creep over time. Operation could continue at steady state, but a shutdown to ambient temperature would result in loose electrical connections. The heater electrical connection system was redesigned to not rely on the clamping force of a fastener through the body of the Borelectric heater, rather, the preload force came from a spring located outside the thermal insulation, thereby placing it in a relatively cool location.

As higher-temperature operation was enabled, it was found that full-temperature, full-power operation was not possible due to the temperature of the pressure vessel. The temperature of the pressure vessel was found to be a good indicator of the temperature of the linear alternator, and it was evident that the temperature of the alternator was nearing the temperature limit of the permanent magnets. Data were recorded, and analysis indicated that the desired thermal conditions could be reached with larger radiator panels installed on the cold flanges and with the emissivity of the pressure vessel increased by surface treatment. The experiment was shut down at about 4,300 hr, the larger radiator panels were installed, and the pressure vessel was covered with Kapton (DuPont) tape to increase emissivity. With the heater at 500 °C, the resulting cold-end and pressure vessel temperatures indicated that proper temperatures would result if the heater were at 650 °C. Therefore, the TDC's were baked out for a high purity fill with helium. After 5,200 hr of operation in thermal vacuum, the temperatures were increased to the design point of 630 °C hot-end temperature and 70 °C cold-end temperature, with power output of about 63 W per convertor.

TDC's #5 and #6 have continued to operate and have accumulated over 8,700 hr of extended operation in thermal vacuum. The test is scheduled to be terminated around the 10,000-hr mark. Since the thermal operating conditions were resolved, performance over the last 2,800 hr has been constant. While much of the operation was at conditions with lower hot-end temperatures than the design point, the components were mechanically stressed, as they would be at full power. During the periods with reduced power output, the amplitudes of the moving components were generally at full-design condition. The performance of TDC's #5 and #6 are summarized in figure 7 and the events are listed in table 1. All of the issues encountered to date with operating TDC's #5 and #6 in the thermal vacuum facility have originated from extended operation of the thermal vacuum facility itself or from the supporting control systems; none have originated from the TDC's themselves.

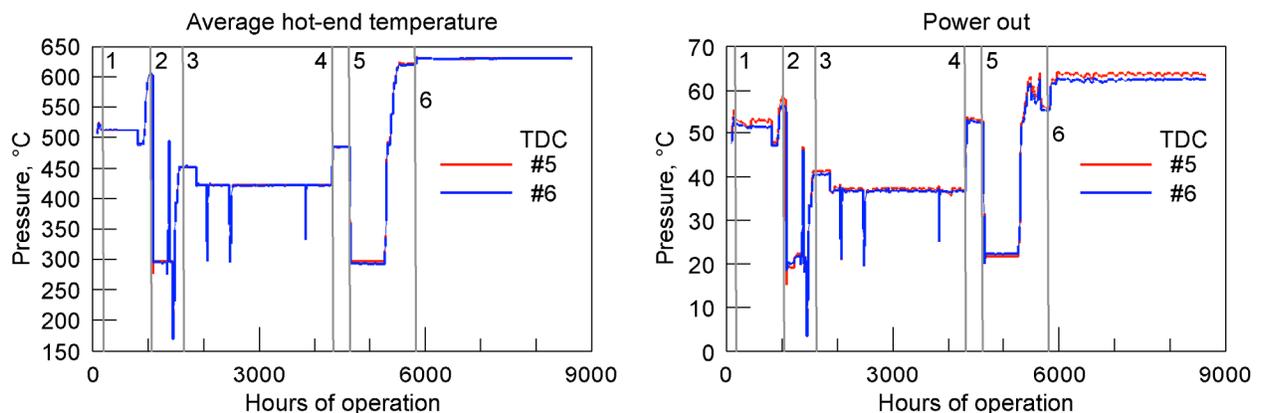


Figure 7.—Performance of TDC's #5 and #6 operating in extended operation in the thermal vacuum environment at GRC.

TABLE 1.—LIST OF EVENTS IN OPERATION OF TDC'S #5 AND #6 IN THERMAL VACUUM

| Time, hours | Event   |
|-------------|---|
|             | Initial operation, stay below regenerator oxidation temperature   |
| 1,083       | Heater electric connection failed                                 |
| 4,320       | Hardware improvements to heaters, radiators, and pressure vessels |
| 4,637       | Bake out  |
| 5,309       | Start to increase hot-end temperature                             |
| 5,842       | Reached full design hot-end temperature                           |

**C. Operation of TDC's #15 and #16**

TDC's #15 and #16 were received at GRC in February 2005. They were installed on a test stand and operational by March of that year. Operation was initially limited to the low-temperature operating point of 500 °C hot-end temperature since these convertors had not been baked out to eliminate residual oxygen. It had been planned to hermetic seal weld these TDC's in mid-2005, so operation was allowed to continue at the low-temperature operating point until hermetic seal welding had been completed. Bake out and subsequent operation at high temperature were scheduled for after completing the hermetic seal weld. TDC's #15 and #16 operated until October 2005 when they were shut down with approximately 4,400 hr accumulated.

The convertors were hermetic seal welded at EWI and returned to operation at GRC in December 2005. Performance after the weld was found to be nominally the same as before the weld. The convertors were then shut down for bake out to remove any residual oxygen. Bake out lasted approximately 250 hr and reached a total pressure of  $2.3 \times 10^{-7}$  torr, greater than an order of magnitude less than had been achieved in 500 hr with TDC's #13 and #14 in their original bake out. Total pressure measured during the bake out is shown in figure 8 compared to the total pressure measured for TDC's #13 and #14. It is believed that this more rapid bake out to lower levels of pressure is the result of low-temperature operation.

TDC's #15 and #16 were filled with high-purity helium and prepared for operation at the design temperatures of 650 °C hot-end temperature and 80 °C cold-end temperature. Operation was restarted at the low-temperature operating point and appeared to be nominal, so the temperatures were increased to the design point. In less than 100 hr, one of the ten heaters on TDC #16 failed. While the TDC was shutdown to investigate the cause of the failure, a second heater on TDC #16 failed. Since it would not be possible to maintain an acceptable temperature profile around the heater head of TDC #16 with two adjacent heaters failed, it was decided that the heaters would be replaced. It was speculated that the heaters failed due in part to the handling during hermetic seal welding and the transients in operating conditions. Therefore, it was decided that all 20 heaters on the pair of TDC's would be

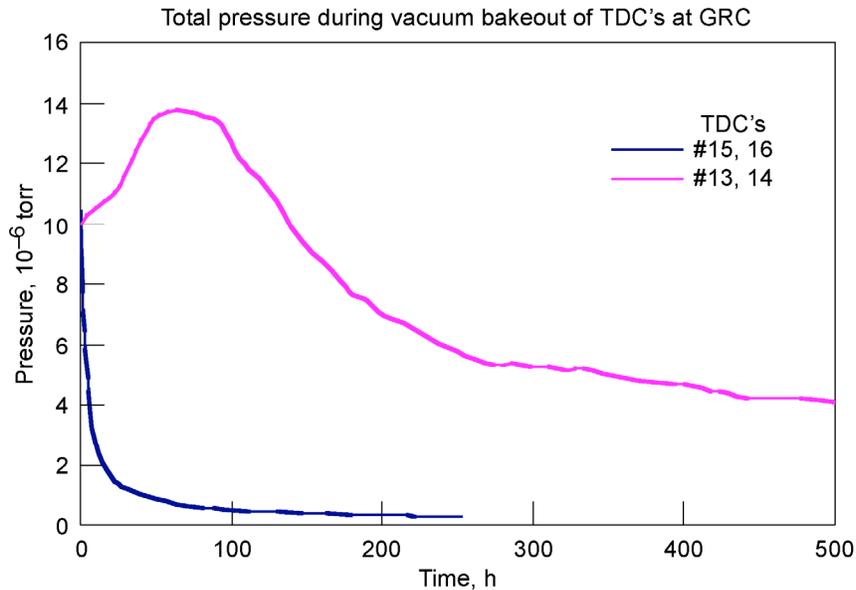


Figure 8.—Bake out results for TDC's #15 and #16 compared to results for #13 and #14.

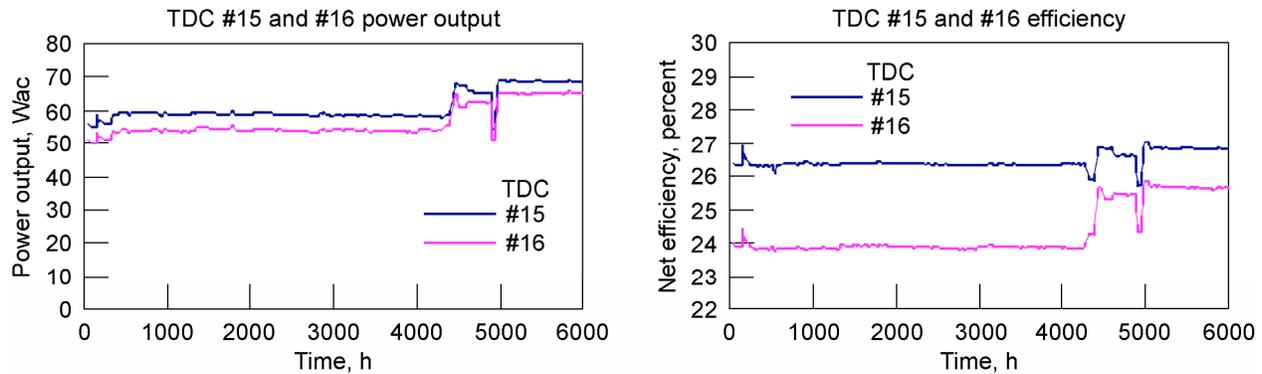


Figure 9.—Power and efficiency of TDC's #15 and #16 during extended operation test at GRC.

replaced. To eliminate the possibility of putting side loads on the heater head, a hydraulic tool was designed that could push the heater cartridge out of the nickel conduction block without putting torsional or lateral loads on the heater head. It was also found that using a commercial freeze spray to cold shock the heater cartridges helped to break the oxidation bond of the heater cartridges in the nickel block, making removal easier.

The heaters were replaced and operation resumed at design temperatures in March 2006. Operation has continued uninterrupted since that time, and over 6,500 hr of operation have been accumulated. Some of the data from TDC's #15 and #16 are shown in figure 9. These TDC's were never operated at GRC at high temperature prior to hermetic seal welding and bake out, where oxygen that might permeate inward through the o-rings could react with the regenerator. The working fluid was sampled prior to hermetic seal welding, and no oxygen was evident. However, at the reduced temperatures, the permeability of the o-rings is reduced and less gas can permeate in either direction. The only conditions when permeation through the o-rings was a concern were when the o-rings were the full operating temperature of about 80 °C. The data show flat-line performance in both power and efficiency for both convertors. There is a slight difference in the performance, which can likely be attributed to tolerances in the clearance seals. These TDC's were fabricated to exercise the newly established QA system at Infinia, not to maximize performance. There were some known differences in the clearance seals when they were shipped to GRC. The key finding of this data is that there are no effects evident over time. The transient at about 4,400 hr is the shutdown and restart for hermetic seal welding. The small transient at about 4,500 hr is the shutdown and restart for bake out. The transient near 5,000 hr is an adjustment in the operating condition.

Throughout all of the operation of TDC's at GRC, working fluid gas analysis has never shown any data that could be interpreted as evidence of outgassing or decomposition of the organics. Furthermore, the inspection after 19,000 hr of operation of TDC's #13 and #14 showed no evidence of regenerator shedding, even though it is believed that those regenerators were damaged by oxidation during the first 5,000 hr of operation. There have been neither shutdowns caused by the TDC's nor any failures of TDC components. All shutdowns and/or failures have been a result of facility-related items.

#### D. Operation of EE-35's

The EE-35 Stirling convertor is a product of Sunpower that was developed under a NASA SBIR. GRC has two convertors that were produced during the SBIR, and four additional convertors that were acquired afterwards. At the nominal operating condition of 650 °C hot-end temperature and 80 °C cold-end temperature, the EE-35's produce about 42 W of electric power output at about 32 percent conversion efficiency. The EE-35 is sized for the heat input of one-half of a GPHS module. A gas bearing system for the power piston and the displacer are used to achieve non-contacting operation of the EE-35 components. This bearing system is similar to the gas bearing system used on all Sunpower commercial cryocoolers, and on the Sunpower cryocooler operating on the RHESSI spacecraft, which has completed over 37,000 hr of operation in space. The EE-35 convertors at GRC have typically not been placed in extended operation as they have often been used for a variety of other tests, including structural dynamic vibration tests, dynamic stability tests to support the SRG110 project, advanced controller tests, and tests for non-NASA customers. The four EE-35's acquired after the SBIR are shown in figure 10, and two of these convertors are shown mounted on a test stand in figure 11. The SBIR units were used for vibration testing and demonstrated flawless operation at vibration levels up to nearly 24 grms, which was the limit of the shake table at GRC. One unit was tested primarily in the axial direction while the other unit was tested primarily in the lateral direction. Approximately 3,500 hr have been accumulated on the EE-35's at GRC to date.



Figure 10.—EE-35 free-piston Stirling converters used for testing at GRC.

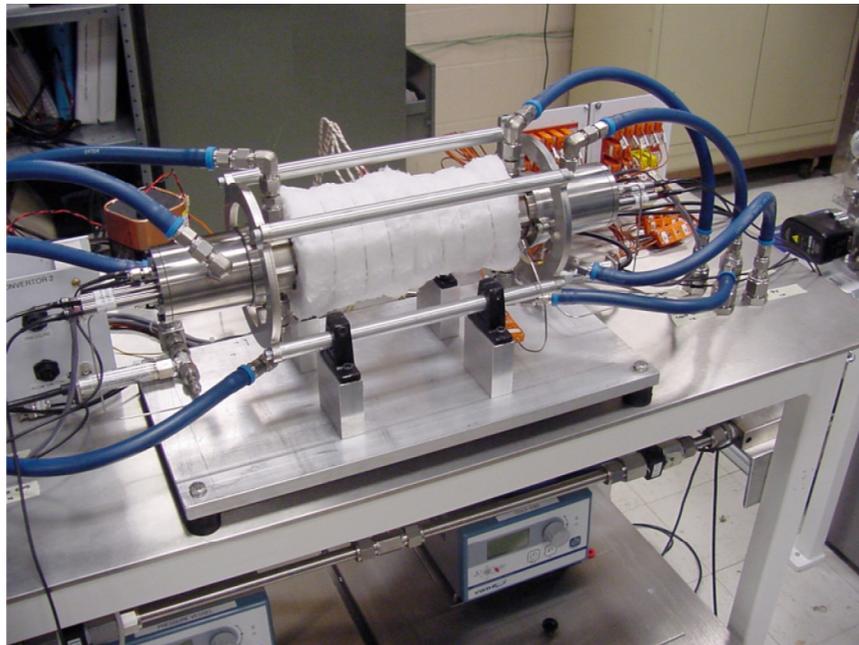


Figure 11.—A pair of EE-35's mounted in the dual-opposed configuration with heater heads inboard at GRC.

### E. Preparation for ASC's

The ASC is being developed by Sunpower under an NRA contract and has been sized for heat input from one GPHS module. The nominal power output is 80 W electric. Non-contacting operation of the power piston and the displacer is achieved by gas bearings similar to those used in the EE-35 design. GRC is preparing for extended operation testing of four ASC's that are being fabricated in support of the Advanced Stirling Radioisotope Generator (ASRG) project. The ASRG project is intended to demonstrate feasibility of a Stirling radioisotope generator with capability for specific power of greater than 7.0 W/kg. Operation of the first two converters will be checked out in air, after which they will be moved to the GRC thermal vacuum facility. This will allow any operational flaws with the facility to be identified, similar to those found with thermal vacuum testing of the TDC's, and then corrected. When the second pair of ASC's is ready for operation, the first pair will be removed from the thermal vacuum facility and returned to operation in air, with the second pair moving into the thermal vacuum facility. The converters are being fabricated with a copper flange at the heat rejection area that can be used either with radiator

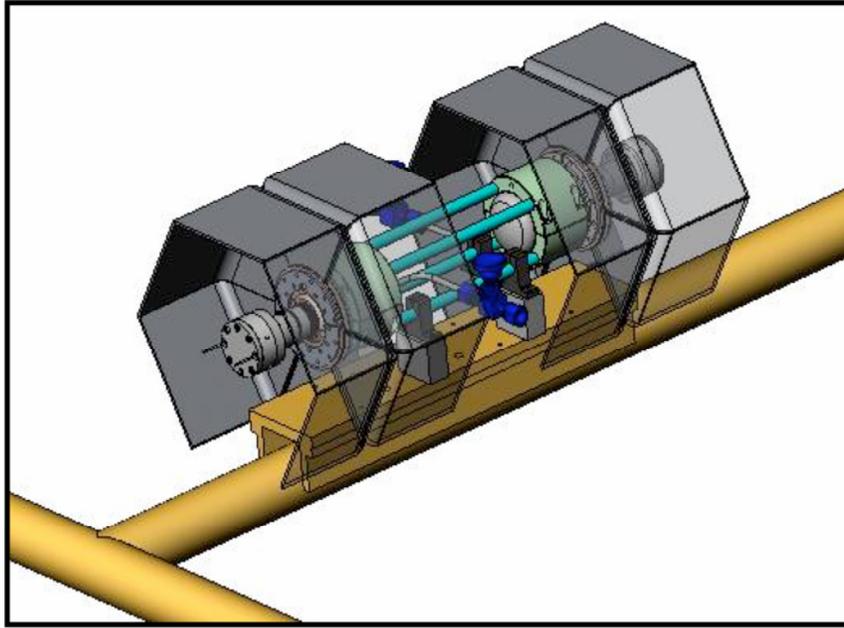


Figure 12.—Conceptual design of ASC thermal vacuum test article for extended operation at GRC.

panels in thermal vacuum, or with cold plates cooled by liquid circulated from a chiller. Both pairs of converters are intended for extended operation, operating continuously unless a focused test is being conducted that precludes unattended operation. The requirements for extended operation of the ASC's are similar to those described for the TDC's with the differences largely being in the physical dimensions and mounting of the hardware, and in the output voltage from the linear alternator, the latter being addressed by the sizing of some components in the controller.

Testing in the thermal vacuum facility will make use of electric heaters to simulate the GPHS modules. Heat rejection will be through radiator panels radiating waste heat to the facility cold walls. This test is slated to use a GRC-developed active power factor correction controller for dual-opposed operation, which eliminates the need for tuning capacitors commonly used to passively correct the power factor. Testing of the ASC's is slated to begin in late 2006. An image of the test article for thermal vacuum operation of the ASC's is shown in figure 12.

#### IV. Conclusion

Extended operation testing of Stirling converters for radioisotope power applications has been conducted at GRC. Stirling converters for this long-life application require non-contacting operation to eliminate any potential wear. Convertors that use flexures to achieve non-contacting operation and convertors that use gas bearings have been under test. Over 80,000 hr have been accumulated with no evidence of wear or degradation inherent in the technology. The only feature that resulted in degraded performance was caused by the use of o-rings as a flange seal that allowed permeation and oxidation; hermetic weld seals would be used in a space power application. TDC's #13 and #14 have accumulated over 21,000 hr of operation; however, the performance was degraded with the aforementioned permeation. TDC's #15 and #16 have been operated in a manner that purposely avoids conditions that lead to permeation and oxidation and have shown no degradation during 6,500 hr of operation. TDC's #5 and #6 have been operated in thermal vacuum for over 8,700 hr with no degradation noted. Preparations are underway to conduct extended operation testing of advanced Stirling converters that make use of gas bearings, with both in-air operation and testing in a thermal vacuum environment.

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| <b>13. ABSTRACT</b> ( <i>Maximum 200 words</i> )<br>The NASA Glenn Research Center (GRC) has been testing free-piston Stirling convertors for potential use in radioisotope power systems. These convertors tend to be in the 35 to 80 W electric power output range. Tests at GRC have accumulated over 80,000 hr of operation. Test articles have been received from Infinia Corporation of Kennewick, Washington and from Sunpower of Athens, Ohio. Infinia designed and built the developmental Stirling Technology Demonstration Convertors (TDC) in addition to the more advanced Test Bed and Engineering Unit convertors. GRC has eight of the TDC's under test including two that operate in a thermal vacuum environment. Sunpower designed and developed the EE-35 and the Advanced Stirling Convertor (ASC). GRC has six of the EE-35's and is preparing for testing multiple ASC's. Free-piston Stirling convertors for radioisotope power systems make use of non-contacting operation that eliminates wear and is suited for long-term operation. Space missions with radioisotope power systems are often considered that extend from three to 14 years. One of the key capabilities of the GRC test facility is the ability to support continuous, unattended operation. Hardware, software, and procedures for preparing the test articles were developed to support these tests. These included the processing of the convertors for minimizing the contaminants in the working fluid, developing a helium charging system for filling and for gas sample analysis, and the development of new control software and a high-speed protection circuit to insure safe, round-the-clock operation. Performance data of Stirling convertors over time is required to demonstrate that a radioisotope power system is capable of providing reliable power for multi-year missions. This paper will discuss the status of Stirling convertor testing at GRC. |   |  |  |  |
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