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## Abstract

The NASA Glenn Research Center has been testing 100-W<sub>e</sub>-class, free-piston Stirling convertors for potential use in Radioisotope Power Systems (RPS) for space science and exploration missions. The present class of free-piston Stirling convertors are capable of achieving high conversion efficiency, making Stirling attractive for meeting future power system needs in light of the limited U.S. plutonium inventory. Convertors currently on test include four Technology Demonstration Convertors (TDCs) manufactured by Infinia Corporation (formerly the Stirling Technology Company), and seven Advanced Stirling Convertors (ASCs) manufactured by Sunpower, Inc. Operation to date has accumulated more than 530 000 hr (60.5 years). Tests have been devised to address the long life performance of Stirling convertors for space applications including in-air extended operation and thermal vacuum extended operation—while other tests have been conducted to characterize Stirling performance in anticipated mission scenarios. Data collected during these tests have been used to support life and reliability projections, drive design changes and improve quality, and prepare for expected mission scenarios. This paper will provide a summary of convertors tested at NASA Glenn and discuss lessons learned through extended testing.

## Introduction

NASA's Glenn Research Center has been involved in the development of Stirling technology since the mid-1970s. Early research and testing included kinematic and free-piston Stirling for a range of applications including residential heat pumps, terrestrial power generation, nuclear space power, and radioisotope space power with a primary interest in future space power (Schreiber (2006a)). Parallel technology advancement efforts included creating fluid flow and heat exchangers, advancing component technologies, and developing Stirling convertors with elevated temperature capability, enhanced reliability, greater efficiency and reduced mass (Schreiber (2006a)). Since 1999, the focus has shifted to 100-W<sub>e</sub>-class free-piston power convertors for a radioisotope generator.

The Department of Energy (DOE) is managing the development of a 100-W<sub>e</sub>-class multimission radioisotope generator for NASA (Schreiber (2006a)). Lockheed Martin Space Systems (LMSS) of Valley Forge, PA, was selected by DOE as the system integration contractor for the project. Glenn has supplied Stirling convertor expertise and provided the capability for a range of tests involving convertors and components (Schreiber (2006a) and Wong and Cornell (2011)). In addition, Glenn has been asked to provide Independent Verification and Validation of the convertors, which includes verifying performance and reliability through extended operation. Two companies have produced Stirling convertors for potential use in the radioisotope generator. Infinia Corporation, formerly the Stirling Technology Company (STC), of Kennewick, WA, designed and built the Stirling Technology Demonstration Convertors (TDCs) under the Stirling Radioisotope Generator (SRG)-110 program. The TDCs were used to demonstrate the feasibility of free-piston Stirling technology for a Radioisotope Power System (RPS) as the design was matured toward production-level status. However, one metric of interest for space power applications is the specific power of a fully integrated system. The TDCs had a specific power of

about 15 W/kg, which resulted in a system-specific power of about 4 W/kg. Through an SBIR contract, Sunpower, Inc., of Athens, OH, developed the EE-35 Stirling convertor, which was sized for half the heat from a general purpose heat source (GPHS) module and achieved nearly 90 W/kg. The Advanced Stirling Convertor (ASC), which was sized for heat from one GPHS, was also designed by Sunpower and demonstrated a similar specific power. Analysis indicated that an RPS using the ASCs could potentially achieve up to 8 W/kg, which would enable electric propulsion missions (Schreiber (2006b)). Focus has since shifted to development of the ASC under the Advanced Stirling Radioisotope Generator (ASRG) project.

Reliability is an essential requirement of a radioisotope generator for space applications. Potential mission lengths could be as long as 14 years, with an additional 3-year storage life prior to launch. While accelerated life testing is possible at the component level, it is not possible to perform an accelerated life test on an entire convertor. This is because there is no single parameter that influences the life of multiple components. While accelerated life testing at the component level has been performed and life requirements have been met, the remaining challenge is to verify long life of the convertor, in which wear mechanisms have been eliminated by design (Schreiber (2006b)). Since operating convertors for 17 years is not a reasonable option, the approach being taken is to build a database from operating convertors that can be used to support a statistical reliability estimate. A total of 39 free-piston Stirling convertors have operated at Glenn and have accumulated greater than 530 000 hr. Convertors have operated in both thermal vacuum and in-air environments, under launch vibration conditions, along with other tests to investigate specific situations, such as convertor start-stop, static acceleration, and various mission phase simulations. There are currently four TDCs and seven ASCs on extended operation at Glenn representing several developmental stages. This paper details extended operation and summarizes the status of convertors that remain on test. Table 1 summarizes ongoing Stirling convertor operation at NASA Glenn.

## Extended Operation at Glenn

Extended operation is 24-hr/7-day unattended operation of Stirling convertors over a long period of time. Originally, extended operation of the TDCs was intended to be 5000 hr (208 days), but a decision was made to continue the test because of the value for reliability and performance data (Schreiber (2006a)). Glenn has been operating convertors in extended operation since 2002 and has developed and refined the procedures, data systems, and safety mechanisms required for safe and reliable unattended operation.

TABLE 1.—SUMMARY OF ONGOING STIRLING CONVERTOR  
OPERATION AT NASA GLENN AS OF NOVEMBER 2012

Convertor	Supplier	Nominal operating temperatures, hot/cold °C	Nominal per-convertor power output, We	Date initiated, month year	Per-convertor runtime, hr
TDCs #13 and #14 <sup>a</sup>	Infinia	650/80	65	June 2003	72 100
TDCs #15 and #16		650/80	65	March 2005	61 100
ASC-0 #3 <sup>b</sup>	Sunpower	650/90	75	Aug. 2007	32 600
ASC-Es #2 and #3 (ASRG Engineering Unit (EU))		625/70	65	Nov. 2008	29 600
ASC-E #4		650/70	65	Dec. 2009	19 100
ASC-E2 #1		850/50	80	Mar. 2010	15 400
ASC-E2 #4		850/50	80	Aug. 2010	900
ASC-E2 #5		850/50	80	Aug. 2010	14 600

<sup>a</sup>Technology Demonstration Convertor

<sup>b</sup>Advanced Stirling Convertor

There are two procedures that are essential to successful extended operation: (1) Test Rack Checkout and (2) Unattended Shutdown Checkout. Any time a change is made to the power pathway, hardware in the test rack, or the software, these two procedures must be performed. The Test Rack Checkout procedure systematically verifies all connections (heater, power pathway, thermistors, thermocouples, etc.) in the test rack and verifies that all channels are read properly into the LabVIEW (Laboratory Virtual Instrument Engineering Workbench) data system (National Instruments Corporation). The Unattended Shutdown Checkout procedure verifies that the most critical shutdown conditions trigger a shutdown and that the appropriate automated actions are taken. The following limits are verified in the procedure: low rejection temperature, high rejection temperature, high hot-end temperature, low hot-end temperature, high-pressure vessel temperature, excessive vibration or overstroke, and building power loss lasting for more than 5 min. Low charge pressure and high charge pressure are also monitored on non-hermetic convertors. Upper and lower limits can be set in the LabVIEW software for any measured parameter and the action taken when the threshold is crossed can be set to give a warning or initiate a shutdown. Hard-wired safeties are also in place for redundancy. Hot-end temperature limit controllers are typically set 30 °C above the operating point and will disable the heaters in the event that the hot end exceeds the set limit. A fail-safe protection circuit (FPC) will disconnect the convertor from the controller load and apply a fixed load to stall the pistons within one-half of the cycle of operation. The FPC is typically used to monitor piston amplitude with the threshold set 0.5 mm above the operating point; however, it is possible to use the FPC with other dynamic signals such as an accelerometer or load cell, as is the case on the Advanced Stirling Radioisotope Generator Engineering Unit (ASRG–EU). In the event of an automated shutdown, an immediate or a controlled shutdown will be initiated depending on the triggering event. If an FPC trip is detected, the heaters will be disabled, hot-end temperature PIDs set to 10 °C, coolant circulator set to 25 °C, and the piston amplitude set to zero. All other shutdown events initiate a controlled shutdown where the heaters are disabled, the hot-end PIDs set to 10 °C, the coolant circulator set to 25 °C, and the piston motion is maintained until the average hot-end temperature falls below a user set value listed in the test rack configuration file. All warnings and shutdowns trigger text messages to automatically notify lab personnel. During attended operation the operator can enable the stall load sized to stop piston motion by kill switches on the test rack.

Procedures governing data quality, archiving, and review have evolved and been refined through testing experience. Other papers have been published that describe improvements in the rack, and will not be discussed here. High-quality connections in the electrical power pathway that are not susceptible to changes in resistance are vital to ensure the test rack is not the cause of variations in the convertor performance. Much time has been invested in investigating and resolving such issues to ensure data quality. Each test rack undergoes an annual calibration cycle to ensure data accuracy. Increased data sample rates and regular review have become a requirement. During initial testing, a daily 5-minute average data point was used for tracking trends and reporting performance. After observing variations caused by power pathway connection issues in the test rack and later power variations caused by the convertor, this evolved into saving and reviewing data sampled every 2 sec. In other cases signals such as piston position and alternator parameters are sampled at rates of 50 kHz. High-data-rate oscilloscopes with data saving capabilities were used to collect these data. Currently, 5-min averages are collected hourly, data are sampled at a rate of one-half Hertz are saved and reviewed daily, and a high-data-rate oscilloscope is used when needed. In future test racks a feature will be added to the LabVIEW software to collect select signals at rates up to 10 kHz.

One challenge of extended operation is maintaining a steady operating point throughout the test. The difficulty often stems from the facility and the equipment required to support convertor operation. Coolant circulators used to reject waste heat from the Stirling cycle require regular maintenance (coolant concentration adjustments, fluid replenishment, and filter cleaning) and sometimes need to be replaced. Heater cartridges that supply heat to the Stirling cycle have a limited life and require replacement. Thermocouples can fail and initiate automated convertor shutdowns. Power outages have also initiated shutdowns; however, a 50-kW backup generator, a facility power conditioner, and an uninterruptible power supply for each test station have addressed this issue. Electrical interference with the FPC circuitry

and facility temperature variations have also caused disturbances. For test articles that are not hermetically sealed, regular charge pressure top-offs are required and often results in a “saw-tooth” pattern in the data. More frequent circulator top-offs, concentration adjustments, and charge pressure top-offs can be performed to minimize the impact on the data.

### Extended Operation of Technology Demonstration Convertors

The TDCs were built as part of the SRG110 program by the Infinia Corporation. A total of 16 TDCs were built in the developmental stages, and there are currently four under extended operation testing at Glenn (Schreiber (2006a)). The TDC was designed to produce a nominal 65 W of electric power when provided <250 W of thermal heat input from a GPHS module. The nominal operating conditions of the TDC are a hot-end temperature of 650 °C, a cold-end temperature of 80 °C, a pressure vessel temperature of 45 °C, a piston amplitude of 6 mm, and an operating pressure of 365 psig (Roth and Schreiber (2004)). Inconel 718 (Special Metals Corporation) was chosen for the heater head material for its high-temperature capability and available long-term creep data that extended out through tertiary creep (Orti (2011)). Noncontacting operation of the piston and displacer was achieved with a spring flexure-based bearing system to enable long life. A section view of the TDC and a photo of a typical TDC test station are shown in Figure 1 below.

During extended operation testing at Glenn, the TDCs are configured in dual-opposed pairs, with the heater heads outboard, such that the convertors are dynamically balanced. The mounting orientation is horizontal and the test article fixture is isolated from the table with rubber mounts. Heat is input through electric heater cartridges, and heat is rejected at the cold end through an ethylene glycol (EG) coolant loop. A secondary EG cooling loop is used on the pressure vessel to control pressure vessel temperature. TDCs are controlled by a zener diode style controller. Hot-end temperature is measured by five thermocouples and set with the hottest at 650 °C. The cold-end temperature is maintained at approximately 90 °C (Roth and Schreiber (2004)). The pressure vessel temperature is measured by three surface mounted thermocouples. The TDCs are the only convertors on extended operation that still utilize a gas charging system. A gas charging system allows the ability to perform vacuum bakeout, initial pressurization, pressure adjustments, and gas sampling. Since the TDCs are not hermetic, pressure top-offs are required to maintain the charge pressure. Every 1000 hr of operation a gas sample is taken to monitor the working fluid to look for impurities and signs of potential outgassing of the organics. TDCs #13 through #16 are currently on extended operation.

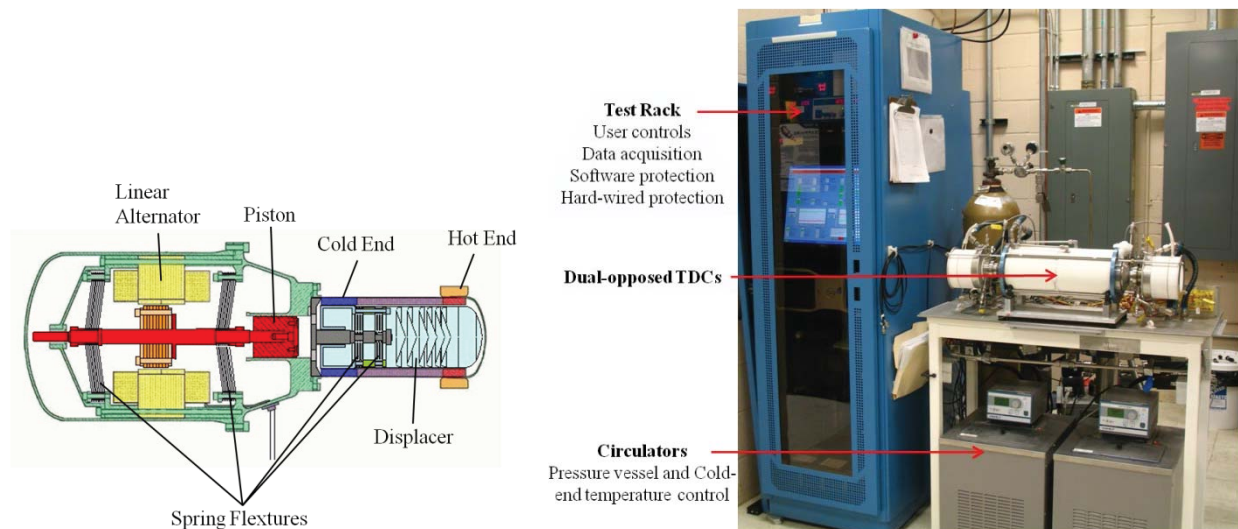


Figure 1.—Section view of Technology Demonstration Convertor (TDC) (left) and photo of typical TDC test station (right).



## Extended Operation of TDCs #13 and #14

TDCs #13 and #14 are the longest running pair of convertors at Glenn, with over 72 100 hr (8.2 years) each. A plot of the convertor performance is shown in Figure 2. These convertors have been previously discussed in references Oriti (2011), Lewandowski and Schreiber (2008), Schreiber (2006a), and Roth and Schreiber (2004). These convertors were the first developed under the Infinia Quality Assurance program and were, therefore, considered flight prototypes (Roth and Schreiber (2004)). These convertors were delivered to Glenn in February 2002, first operated in April 2002, and began extended operation in June 2002. Early stages of extended operation were disrupted by electrical connection issues in the resistance heaters, which were resolved by June 2003. The convertors were not hermetically sealed when manufactured with o-ring seals at flanged joints. While a vacuum bakeout process was used to ensure a high purity helium fill, the o-rings were found to allow helium to permeate out and air to permeate in (Schreiber (2006a)). Oxidation of the regenerator is believed to have caused performance degradation during the first 18 000 hr of operation. Beginning near 18,000 hr, the convertors were operated at a reduced hot-end temperature to prevent further oxidation until hermetic welding of the pressure joints. In January 2007, at approximately 19 000 hr, the pressure joints were welded, but the helium fill tube remained, enabling gas sampling and mean charge pressure adjustments. At 20 000 hr, full-temperature operation was resumed and the observed performance became steady. Subsequent variations in performance did occur, but have been attributed to set point adjustments and facility-related items. The presence of the non-hermetic fill tube introduced the need to make periodic pressure adjustments approximately every 2 weeks, which appear as saw-tooth variations in power output.

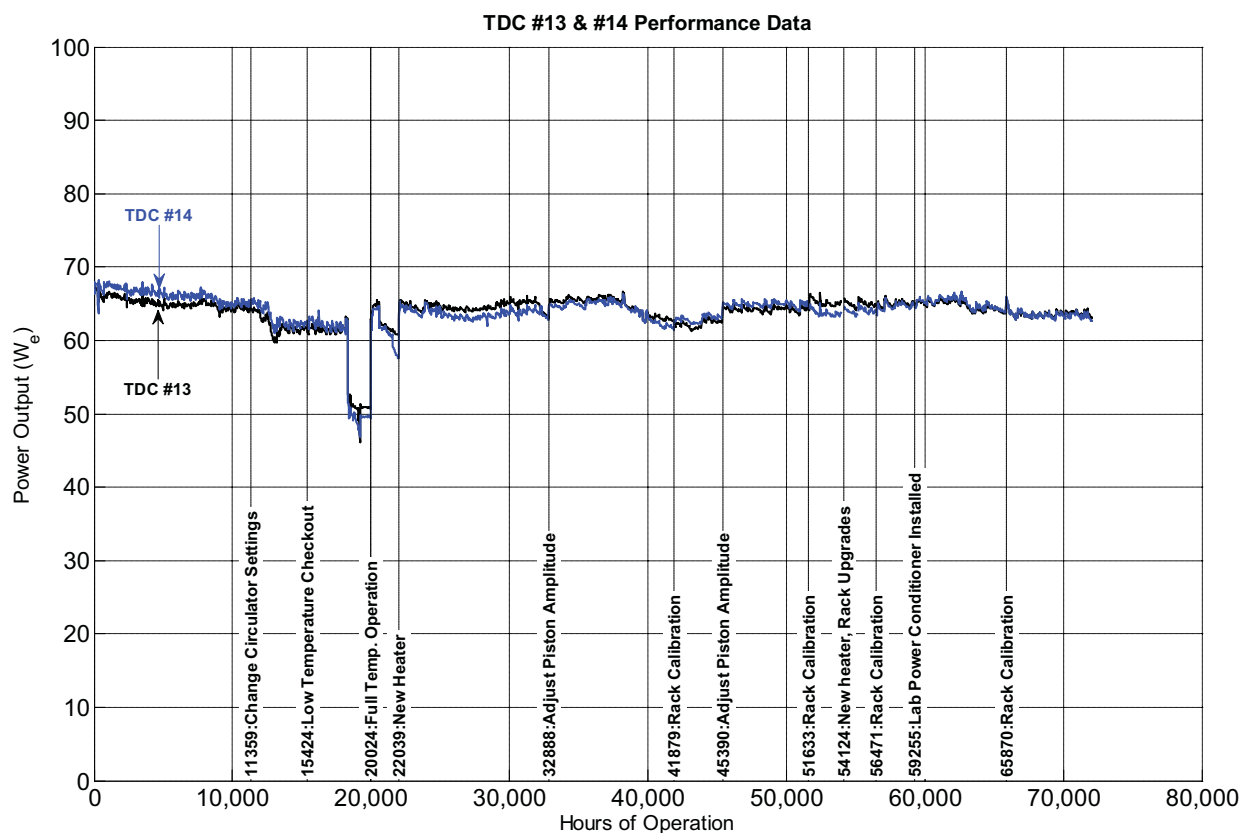


Figure 2.—Technology Demonstration Convertors (TDCs) #13 and #14 performance through 72 100 hr of operation.

Cartridge heaters also introduced performance variability as they degraded and eventually failed. This resulted in a variation of the heat input and therefore, power output from the convertor. The cartridges were replaced at 22 000 and 54 000 hr. Other variations in the performance were the result of manual shutdowns for instrument calibration, manual corrections to piston amplitude for controller drift, facility temperature fluctuations, nuisance trips of the protection circuit, building power outages, and maintenance of the cold-end temperature control system. No evidence of outgassing or decomposition of the organics has been observed in the gas samples taken every 1000 hr of operation, and no unexplainable change in performance have been observed over the entire operation of TDCs #13 and #14.

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

TDCs #15 and #16 are the second longest running pair of convertors at Glenn, with over 62 200 hr (7.1 years) each. These convertors have been previously discussed in the following references: Oriti (2011), Lewandowski and Schreiber (2008), Schreiber (2006a), and Roth and Schreiber (2004). Convertor performance data is shown in Figure 3. These convertors were also developed under the Infinia Quality Assurance program and are identical to TDCs #13 and #14. Upon receipt in February 2005, these convertors were operated at hot-end temperature of 500 °C until hermetic sealing to avoid regenerator oxidation as experienced in TDCs #13 and #14 (Schreiber (2006a)). The convertor pressure vessel joints were welded in the same fashion as TDCs #13 and #14 after 4400 hr of operation. A noticeable performance difference can be observed between TDCs #15 and #16, which is attributed to a known difference in clearance seals. The same sources of operational variation described for TDCs #13 and #14

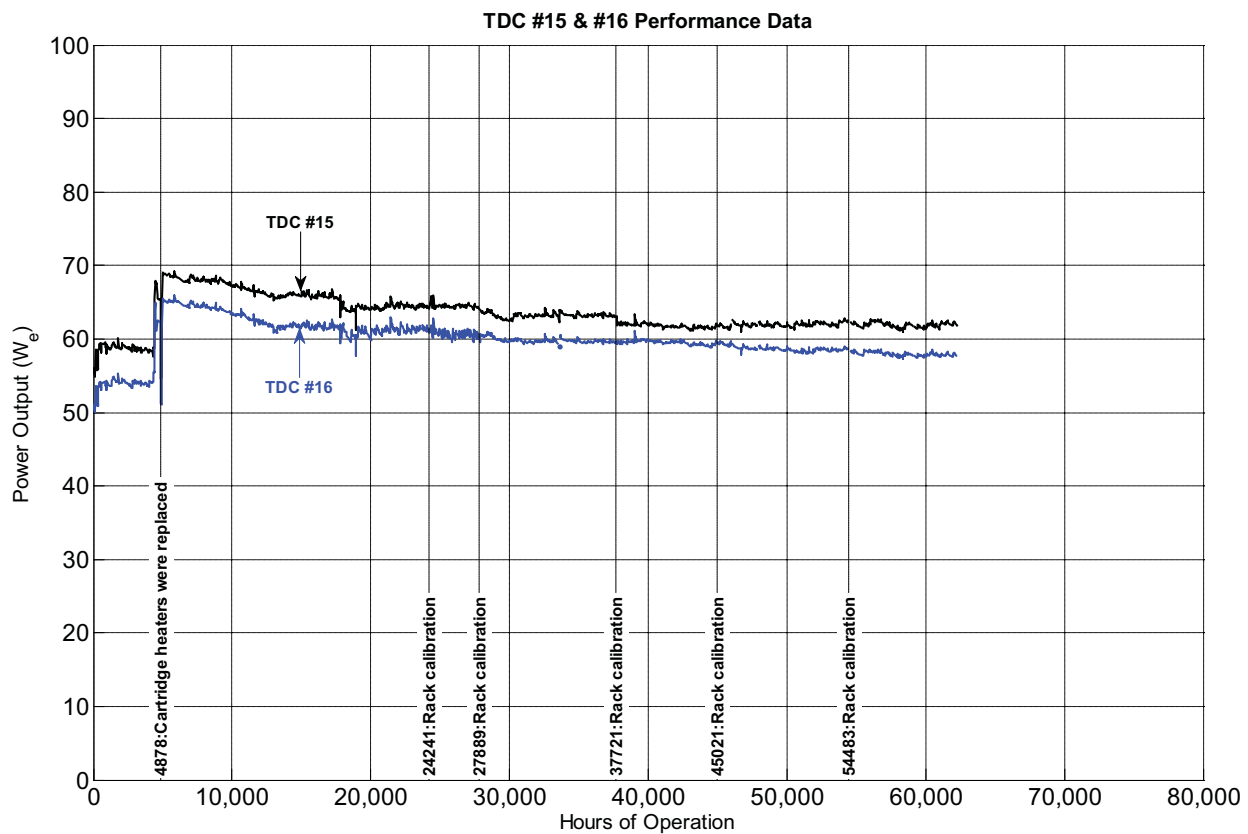


Figure 3.—Technology Demonstration Convertors (TDCs) #15 and #16 performance through 62 200 hr of operation.

also exist for these convertors. Cartridge heater replacement occurred at 4900 hr and was attributed to improper cleaning after the cartridge lead wire braze operation; however, this issue was corrected for the replacement cartridges. A slight decrease in performance from 5000 to 15 000 hr was attributed to variations in the cold-end temperature control. An open-bath circulator is used to flow a water-glycol mixture around the heat rejection zone of the convertor. This method is susceptible to changes in concentration as water evaporates, which affects the viscosity and fluid flow, and thus the cold-end temperature. Care has been taken to make periodic adjustments to the circulator fluid to maintain constant conditions. Periodic adjustments are also made to maintain the charge pressure, which results in the saw-tooth variation in the power plot. As with TDCs #13 and #14, no evidence of outgassing or decomposition of the organics has been observed in the gas samples, and no unexplainable degradation in performance has been observed over the entire operation of TDCs #15 and #16.

### **Extended Operation of ASCs**

The ASCs were built by Sunpower, Inc., in support of the ASRG project. To date, there have been 21 ASC convertors operated at Glenn for a variety of tests including developmental, investigative, and extended operation tests. The ASCs cover a range of maturation stages from technology development (ASC-1, ASC-0, and ASC-1HS), engineering model (ASC-E, ASC-E2, and ASC-E3), and flight (ASC-F). Sunpower delivered the following under the Glenn development contract: ASC-1, ASC-0, ASC-1HS, ASC-E, and ASC-E2 (Wong and Cornell (2011)). The ASC-1s were the first in the sequence and demonstrated a conversion efficiency of 38 percent and the ability to achieve hot-end temperatures up to 850 °C by utilizing MarM-247 as the heater head material (Oriti (2011)). However, the design included nine o-ring seals, which was not acceptable for extended operation due to working gas permeating through the seals (Lewandowski and Schreiber (2008)). The ASC-0s were then developed as hermetic units (meaning the pressure joints were welded) with the exception of the helium fill tube, which allowed for gas sampling and charge pressure adjustments. Because a process had not yet been developed for hermetically sealing a MarM-247 heater head, Inconel 718 was used and the design was given a preceding model number. The ASC-1HS units then concluded the technology development stage with high-temperature MarM-247 heater heads and hermetic sealing with the exception of the fill tube. The ASC-E convertors were designed for integration into the ASRG-EU to expedite demonstration of a generator. These convertors utilized an Inconel 718 head and were the first to undergo complete hermetic sealing via pinching the fill tubes. Integration of the ASC-E units into an engineering unit generator required development of a comprehensive product specification, including generator interfaces and preliminary flight requirements, improved quality assurance, documentation, and processing and testing of the convertors. This build greatly advanced the state of the technology. The ASC-E2s were built under a newly developed Quality Management System. The ASC-E3 design is the last build prior to qualification and flight hardware (Wong and Cornell (2011)). A section view of the ASC and a photo of an ASC single convertor test station are shown in Figure 4.

### **Extended Operation of ASC-0s #3 and #4**

ASC-0s #3 and #4 were delivered to Glenn in July 2007 and have accumulated 32 600 and 25 860 hr (3.7 and 3.0 years), respectively. These convertors have been previously discussed in Oriti (2011) and Cornell et al. (2008). These convertors have operated in-air since delivery and their performance is shown in Figure 5. The convertors produce approximately 75 W<sub>e</sub> at operating temperatures of 650 °C hot end and 90 °C cold end. After 282 hr at low-temperature operation, the convertors operated at the nominal 650 °C hot-end temperature until approximately 3990 hr. At this time, the convertors were shut down for rack maintenance and calibration. The performance then became more variable as the result of a poor electrical connection in the test rack, which occurred during the rack maintenance. After 7400 hr, the convertors were exposed to 8.7 g<sub>rms</sub> random vibration in all three axes to simulate launch vibration. After vibration testing, heater head diameter measurements were taken to characterize Inconel 718 creep. A laser

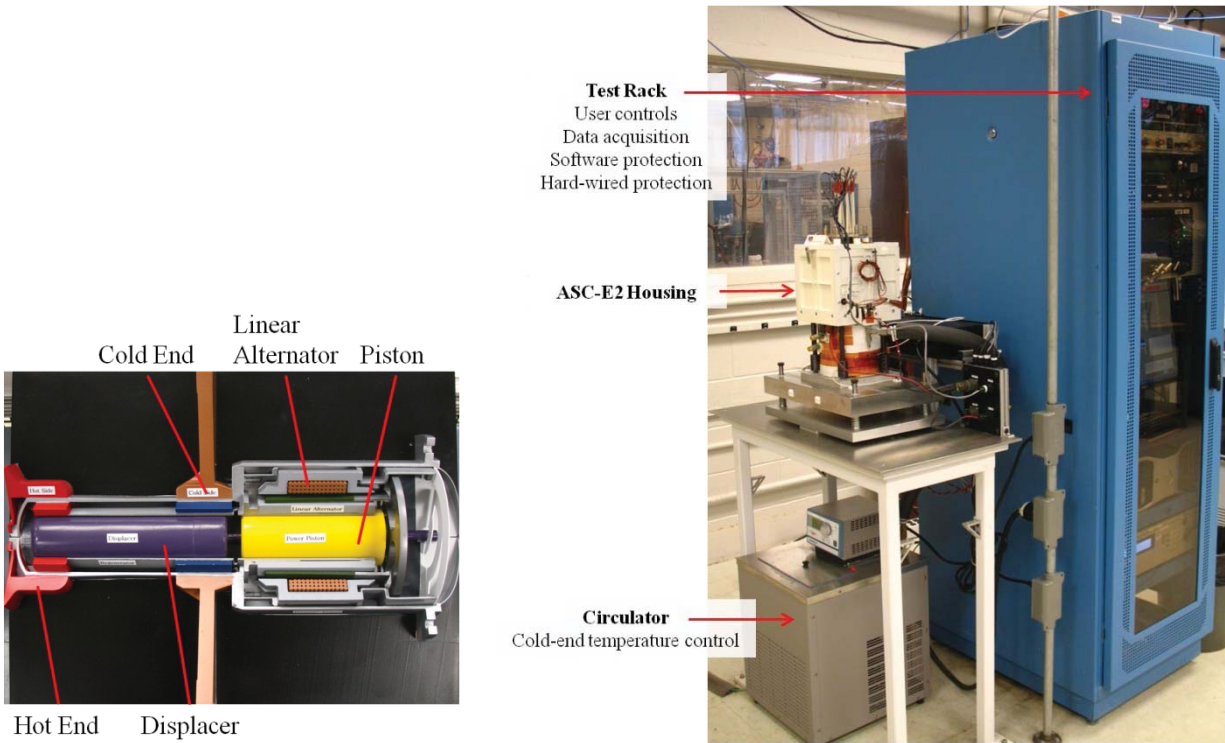


Figure 4.—Section view of Advanced Stirling Converter (ASC) (left) and photo of ASC single convertor test station (right).

micrometer with resolution of  $0.05 \mu\text{m}$  was used to measure the diameter as a function of axial position at eight circumferential locations. These same measurements will be taken in the future to quantify creep. From 7400 through 14 400 hr, an investigation took place to find the source of the faulty power pathway connection in the test rack; however, the variable nature of the power output continued and no root cause was identified. The final step of the hermetic sealing process was completed after 14 400 hr as the fill tubes were pinched. The convertors were leak tested before and after the fill tube pinch, and in both cases the leak rates were below the flight requirement. Converter performance after the fill tube pinch was evaluated and there was no loss in performance. At 14 900 hr, rack maintenance and calibration was performed. Afterwards, the converter performance was more steady, further suggesting a link between performance variability and the test rack. Following rack maintenance at 18 200 hr, variable converter performance returned. At 23 250 hr, the test rack was upgraded to a design with a more robust power pathway. Since the rack upgrade, converter performance has been more stable suggesting a component or connection in the test rack was responsible. Random performance variations on the order of  $0.2 W_e$  were observed on ASC-0 #4 after the rack upgrade and it is suspected to be the result of poor connections at the electric feedthrough pin of the convertor. Connections at the feedthrough pins were nonstandard sleeves that slip over the pin. At 25 848 hr, a soldering procedure with known risk was performed to improve these electrical connections. During the soldering process, an internal short occurred on ASC-0 #4, rendering it inoperable. As a result, this soldering procedure was not performed on ASC-0 #3. ASC-0 #3 was returned to extended operation as a single convertor in the vertical orientation. Between 28 485 and 28 557 hr, an unexplained increase in piston amplitude of  $\sim 0.02 \text{ mm}$  was observed. Since the ASC-0 #3 feedthrough connection was not soldered, the piston amplitude variation could potentially be the result of a poor connection. Near 29 109 hr, a test was performed to measure the natural frequency while operating. Other factors influencing the steady operation include circulator fluid adjustments, ambient temperature changes, facility power outages, and nuisance shutdowns due to instrumentation. While

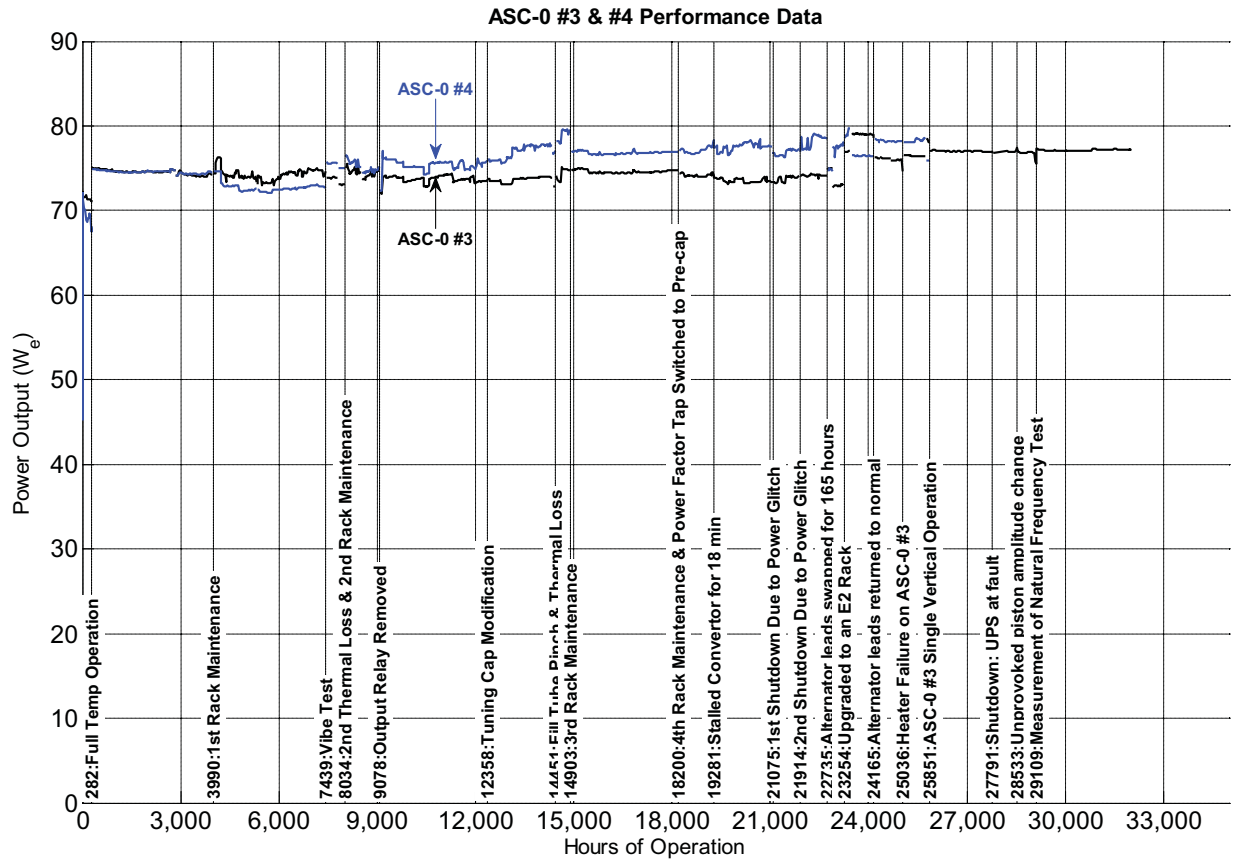


Figure 5.—Advanced Stirling Convertors (ASC)—0s #3 and #4 performance through 32 300 and 25 860 hr of operation, respectively.

variations in power output and piston amplitude have been observed in the short term and attributed to a poor feedthrough connection, no degradation in performance has been observed over the long-term operation of ASC—0s #3 and #4.

### Extended Operation of the ASRG—EU (ASC—Es #2 and #3)

The ASRG—EU is the first integrated generator to be tested at Glenn. The ASRG has been previously discussed in Oriti (2011) and Cornell et al. (2008). It was designed and fabricated by the LMSS under contract to DOE and integrates two ASC—Es in a dual-opposed configuration. The ASC—Es utilized an Inconel 718 head, which allow hot-end temperatures of up 650 °C. After undergoing several system-level tests to qualification-level thermal and dynamic environments at LMSS, the ASRG—EU was delivered to Glenn in August 2008. The EU is operating in a vertical orientation with heat provided through electric heat sources. Convective cooling is provided to the generator beryllium housing via fans blowing cooled air. The EU has been controlled with both an alternating current (AC) bus control and an early prototype ASC Controller Unit (ACU) delivered by LMSS, which controls the convertors similar to what will be used in flight. The generator has accumulated a total of 30 000 hr of operation at Glenn, with 15 400 of those hours under ACU control. Converter performance for the ASRG—EU convertors is shown in Figure 6. The convertors produce approximately 65 W<sub>e</sub> at operating temperatures of 625 °C hot end and 63 °C cold end. The generator was operated on AC bus control during the first 5200 hr, during which time variations in converter performance were observed and attributed to variations in the test rack power pathway impedance. Test rack upgrades were made at 2100 hr and 4800 hr. The ASRG—EU operated on the ACU from 5200 to 21 219 hr, with the exception of one brief period where it operated on AC bus

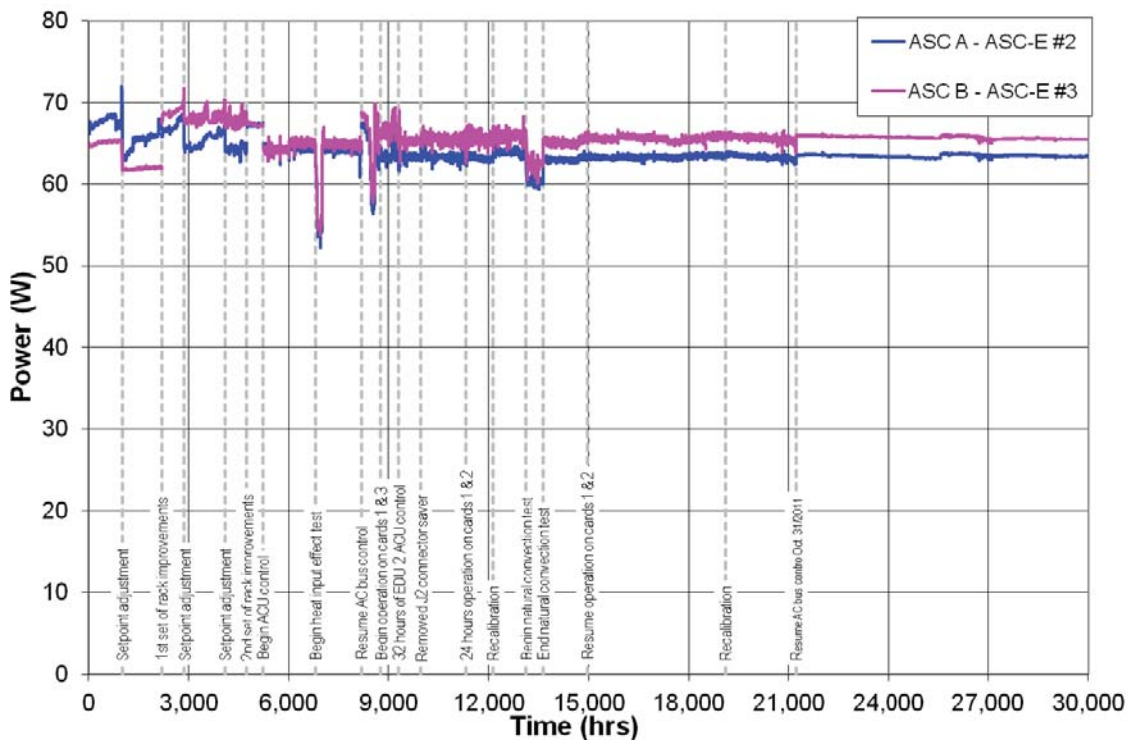


Figure 6.—Advanced Stirling Radioisotope Generator Engineering Unit (ASRG–EU) performance through 30 000 hr of operation.

control for specific tests. Tests were conducted at the request of LMSS between 5200 and 13 500 hr. From 13 500 to 21 219 hr, operation was maintained at the nominal conditions. This region best represents steady-state long-term operation under ACU control and matched well to the initial steady period of ACU operation from 6000 to 8000 hr. This suggests that the system, ASRG plus ACU, responded in a repeatable fashion when returning to the same operating conditions. At 21 219 hr, control of the ASRG–EU was changed from ACU to AC bus control. The apparent performance change at that time is attributed to a known issue in the ACU control algorithm that results in jitter, or what appears as random variations in the piston amplitude. From 21 219 hr to present, the ASRG–EU has been operating under AC bus control and the power output has been steady. During this period of AC bus control, disturbances to steady operation include a rack recalibration and ambient temperature variations.

#### Extended Operation of ASC–Es #1 and #4

ASC–E #1 was fabricated in support of the ASRG–EU, but not integrated into a generator system. ASC–E #4 was later fabricated from spare parts and included updates intended for E2s. These two convertors were delivered to Glenn and began extended operation in December 2009 where ASC–E #1 has accumulated 10 381 hr and ASC–E #4 has accumulated 19 100 hr of operation. These convertors underwent heater head diameter measurements for evaluation of long-term creep of Inconel 718 on an operating convertor. They were previously discussed in Oriti (2011) and Cornell et al. (2008). A summary of convertor performance for the ASC–Es #1 and #4 convertors is shown in Figure 7. The convertors produce approximately 65  $W_e$  at operating temperatures of 650 °C hot end and 70 °C cold end. At around 1000 hr of operation, the voltage tap for the convertor power output measurement was moved to the convertor side of the tuning capacitors. The power measurement shows this shift, which is caused by the resistive loss that exist between the two points. Near 4500 hr, a 7- $W_e$  drop in power output was observed on ASC–E #1. The power path was inspected for loose connections, but none were found. Operation

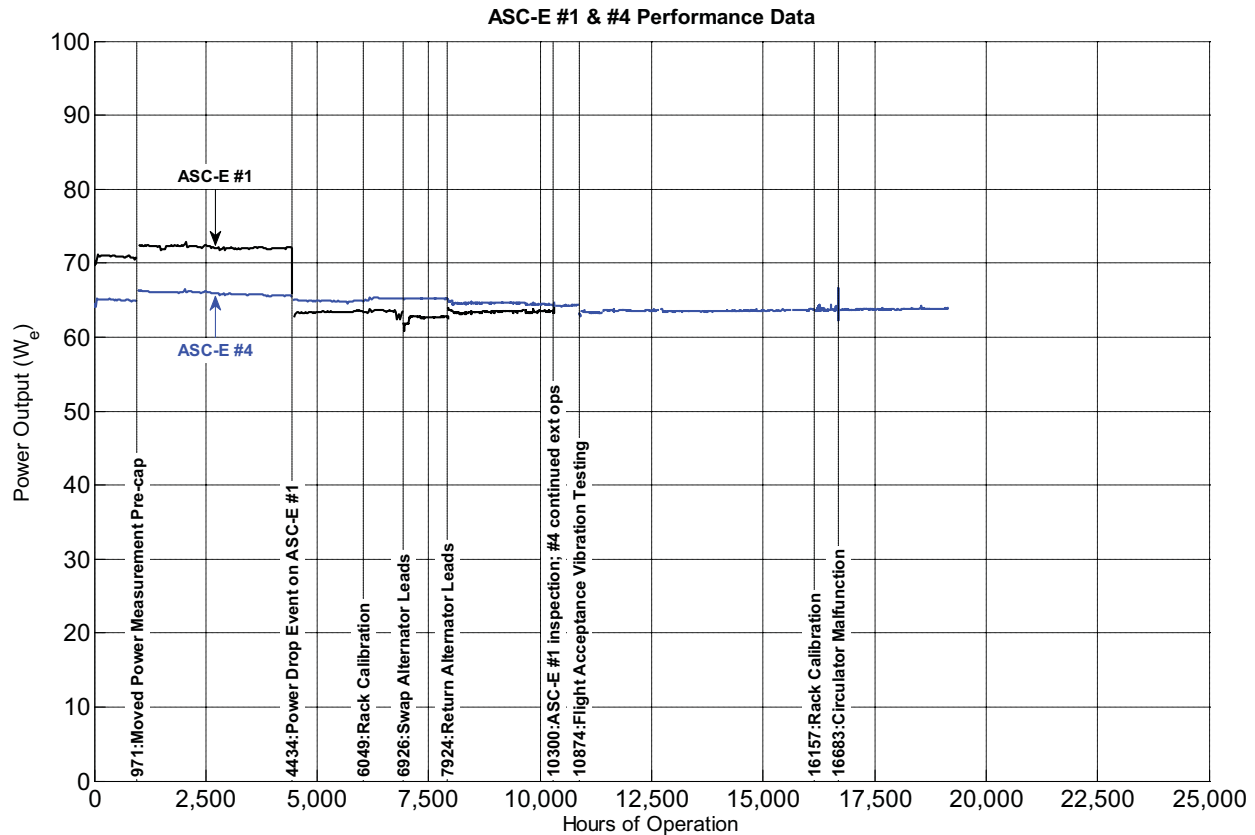


Figure 7.—Advanced Stirling Convertor (ASC)—Es #1 and #4 performance through 10 381 and 19 100 hr of operation, respectively.

resumed and ASC-E #1 never returned to its original power level. Between 7000 and 8000 hr, the convertors operated with the alternator leads connected to opposite sides of the test rack to determine if the power loss was the result of a faulty connection in the test rack or an issue on the convertor side of the alternator connection. At 10 381 hr of operation, ASC-E #1 was removed from operation and an inspection was performed to determine the root cause of the power loss. Upon disassembly, it was found that the piston was rubbing on an out-of-round and undersized cylinder, which liberated metallic debris. The debris blocked gas bearing flow passages and caused improper check valve operation. This resulted in a change in piston mean position and backflow through the check valve. The calculated power loss from these changes approximately matches measured power loss experienced during testing. ASC-E #4 has continued operation in a single, vertical configuration. Between 10 400 and 10 850 hr, characterization testing was performed on ASC-E #4 in its new configuration and consisted of measurements of convertor natural frequency, acoustic emissions, and vibration. These measurements were taken to serve as a baseline for comparison to future measurements for health monitoring purposes. Between 10 874 and 10 901 hr, launch simulation and flight acceptance vibration tests were performed. Vibration levels of 15.8  $g_{rms}$  in the axial direction, and 8.9  $g_{rms}$  in the lateral directions were achieved. At 16 683 hr, the circulator, which cools the cold-side adapter flange (CSAF), malfunctioned causing a disturbance to the operating point. Other variations in power output have been attributed to shutdowns and fluctuations in ambient temperature. In particular, between 16 000 and 16 800 hr, the air conditioning in the Stirling laboratory malfunctioned.

## Extended Operation of ASC-E2 #1

ASC-E2 #1 is the longest running E2 convertor at Glenn, with a cumulative runtime of 15 400 hr. This convertor was previously discussed in Oriti (2011) and Oriti and Wilson (2011). ASC-E2 #1 was delivered to Glenn in April 2010 with a known heater head flaw that results in helium leakage. Convertor performance is shown in Figure 8. The majority of this operation was at 850 °C hot end and 50 °C cold end, which corresponds to the beginning-of-mission low-rejection (BOM-LR) condition as defined per the E2 product specification. ASC-E2 #1 completed performance mapping, initial extended operation, and frequency sweep tests during the first 888 hr. ASC-E2 #1 was then paired and operated in the dual-opposed configuration with ASC-E2 #2 for electromagnetic interference characterization from 888 to 1143 hr. ASC-E2 #1 was then fitted with a “compact” heat source and returned to operation in the single vertical orientation. The compact heat source was installed to investigate environmental losses and better quantify net heat input to the convertor. Its design reduced thermal losses through the insulation relative to the standard heat source used for ASC-E2 operation. The baseline ASC-E2 heat source losses were approximately 170  $W_{th}$  at 850 °C hot-end temperature, while the compact heat source losses were 75  $W_{th}$ . Performance mapping with the compact heat source took place between 1143 and 1476 hr. Extended operation at the BOM-LR temperature began immediately after performance mapping and steady conditions were maintained between 1476 and 3849 hr. During this time, a downward trend was observed in the power output as a result of the helium leakage. On two occasions (at 2692 and 3223 hr) corrections were made by increasing the piston amplitude to return to the baseline BOM-LR power output. Between 3849 and 4696 hr, another off-nominal operating condition test was performed. At 4696 hr the compact

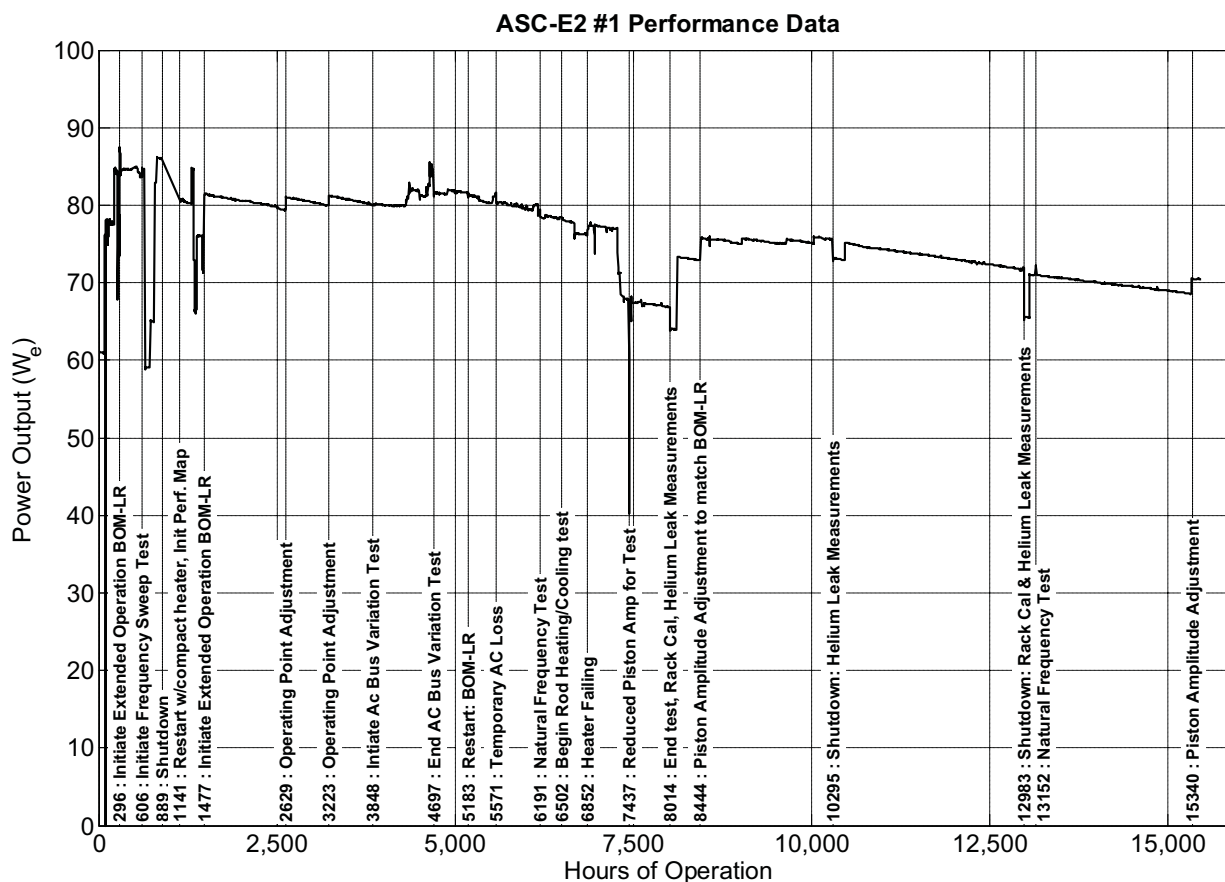


Figure 8.—Advanced Stirling Convertor (ASC)-E2 #1 performance through 15 400 hr of operation.



heat source failed and was replaced with a standard ASC-E2 heat source. From 4696 to 6097 hr, operation continued at the BOM-LR conditions. The downward trend in power output continued, but was more variable due to nuisance shutdowns and temporary disturbances in the ambient temperature. Between 6097 and 6193 hr, a test was performed to experimentally measure convertor natural frequency while operating. Performance data from ASC-E2 #1 are being used to validate predictions of power loss versus time due to helium leakage, and periodic tests to experimentally measure the convertor natural frequency are being performed as a metric to track the effect of helium leakage. Other natural frequency tests were performed near 8015 and 13 152 hr. A plot showing measured performance and Sage predicted performance versus time is shown in Figure 9. The initial assumptions used in the Sage model under predicted the performance of the convertor by 1 to 4 W depending on the leak rate used; however, the measured data appears to follow the trend predicted by Sage for a leak rate of  $9 \times 10^{-6}$  std cc/sec. Between 6500 and 8015 hr, another off nominal operating condition test was performed. From 8114 to 10 295 hr, operation continued at the BOM-LR conditions. The piston amplitude was adjusted to match the BOM-LR condition at 8444 hr. At 8576 hr, an ambient temperature disturbance caused the power output to change. The downward trend continued as helium was lost and several adjustments to piston amplitude were made to maintain a nominal value of 4.20 mm. During this period the piston amplitude was adjusted only to maintain amplitude and not to match the original power output for this operating condition. At 10 295 hr, the convertor was shut down and helium leak measurements were made as part of the performance prediction effort. Operation then continued at the BOM-LR condition from 10 450 to 12 983 hr at which time the convertor was shut down for an annual rack calibration and another helium leak measurement. Operation continued at the BOM-LR condition from 13 000 to 15 400 hr at which time the piston amplitude was adjusted to return to 4.20 mm.

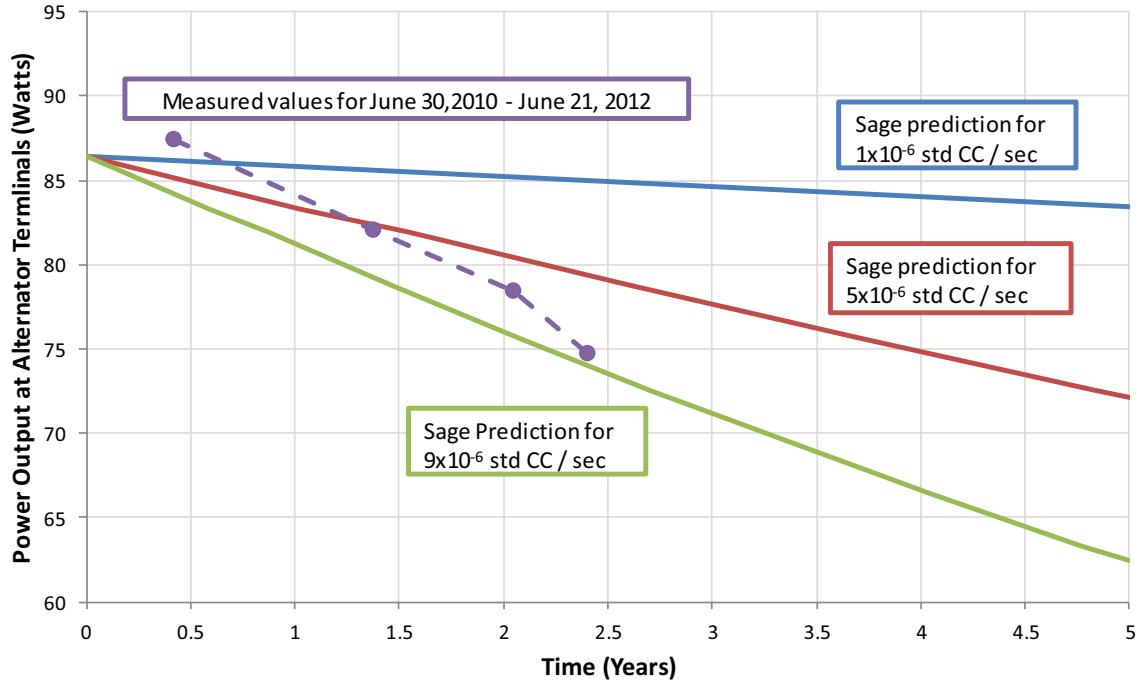


Figure 9.—Sage predicted power output at the alternator terminals over time for various leak rates compared to measured data.

## Extended Operation of ASC–E2s #5 and #6

The third pair of ASC–E2 units, #5 and #6, was delivered to Glenn in July 2010. These convertors were previously discussed in Oriti (2011) and Oriti and Wilson (2011). A plot of convertor performance is shown in Figure 10. These convertors were operated as a pair in the dual-opposed vertical orientation until 7184 hr. Between 0 and 1194 hr, checkout testing and performance mapping were completed. Extended operation, at the baseline BOM–LR condition as defined in the E2 product specification, began immediately after performance mapping. Between 1194 and 1914 hr, an increase in power output was observed and has been attributed to changes in fluid concentration in the cold-end circulator. This is because a specific mixture of glycol and water was required to achieve the desired temperatures during performance mapping. During extended operation the water slowly evaporated, altering the fluid viscosity and thermal characteristics. At the 1914 hr mark, adjustments were made to the circulator fluid temperature and concentration to maintain the BOM–LR condition. Between 2202 and 2323 hr, an off-nominal test was performed during which the alternator housing temperature was varied. Between 2323 and 2833 hr, the convertors were operated at the end-of-mission (EOM) LR condition, which resulted in a lower power output, as expected. Near 2480 hr, the ASC–E2 #5 heat source began to fail and completely failed at 2665 hr, which resulted in the fluctuations in power output near that time. Between 2883 and 4233 hr, operation at the high rejection temperature was explored for both BOM and EOM conditions to ascertain its effect on convertor performance. During this time, the convertor performance was less steady, which has been attributed to the previously described variability in rejection temperature control. At high rejection temperature, the circulator bath requires more frequent adjustments to maintain steady conditions. Several manual adjustments were made around the 3019 hr of operation. Near 3823 hr, a large disturbance in ambient temperature resulted in the observed performance variation. Between 4233 and 6776 hr, the operating condition was maintained at the baseline BOM–LR condition. Near 6460 hr, the heat sources on both convertors began to fail. The dip in power near 6600 hr has been attributed to simultaneous heater cartridge failures in both heat sources. At 6776 hr, the hot-end temperature was lowered from 842 to 760 °C to extend heater life. Between 6776 and 7208 hr, alternator housing temperatures were varied and rejection temperatures for both EOM and BOM conditions were explored to determine their effect on convertor performance and measure forces transmitted through the CSAF. At 7208 hr, ASC–E2 #6 was removed from operation for an inspection. Further detail is given on this later in the paper. At this same time the test rack was calibrated, a new heat source was installed on ASC–E2 #5, and #5 was returned to operation as a single convertor. From 7208 to 9507 hr, a modified E3 BOM–LR condition was maintained and the convertor produced approximately 78 W<sub>e</sub> at operating temperatures of 750 °C hot end, 35 °C cold end, and 46 °C alternator housing. From 9507 to 10 671 hr, off-nominal tests were performed to explore a new method for characterizing thermal insulation losses and to simulate convertor performance during expected thermal transients at launch. Operation was then returned to the modified E3 BOM–LR condition and remained at this condition until 11 947 hr with the only exception being an off-nominal test performed around 11 346 hr. During this period, the increase in power output has been attributed to the previously described fluid concentration changes in the cold-end circulator. More off-nominal tests were performed between 11 947 and 12 590 hr to support exploration of simulated launch transients and convertor performance determination. Operation then returned to the modified E3 BOM–LR condition and remained at this condition until 14 609 hr. An increase in power output was observed between 12 590 and 13 773 hr and has been attributed to variability in the rejection temperature control. Adjustments were made to the circulator bath to correct this variability at 13 773 hr. Between 14 609 and 14 686 hr, an off-nominal test was performed where the E3 minimum qualification CSAF and alternator housings were reached, the test rack was calibrated, and ASC–E2 #4 was paired with #5 in a dual-opposed vertical configuration. In future continued extended operation, ASC–E2s #4 and #5 will operate as a pair at the BOM–LR condition per the E3 product specification.

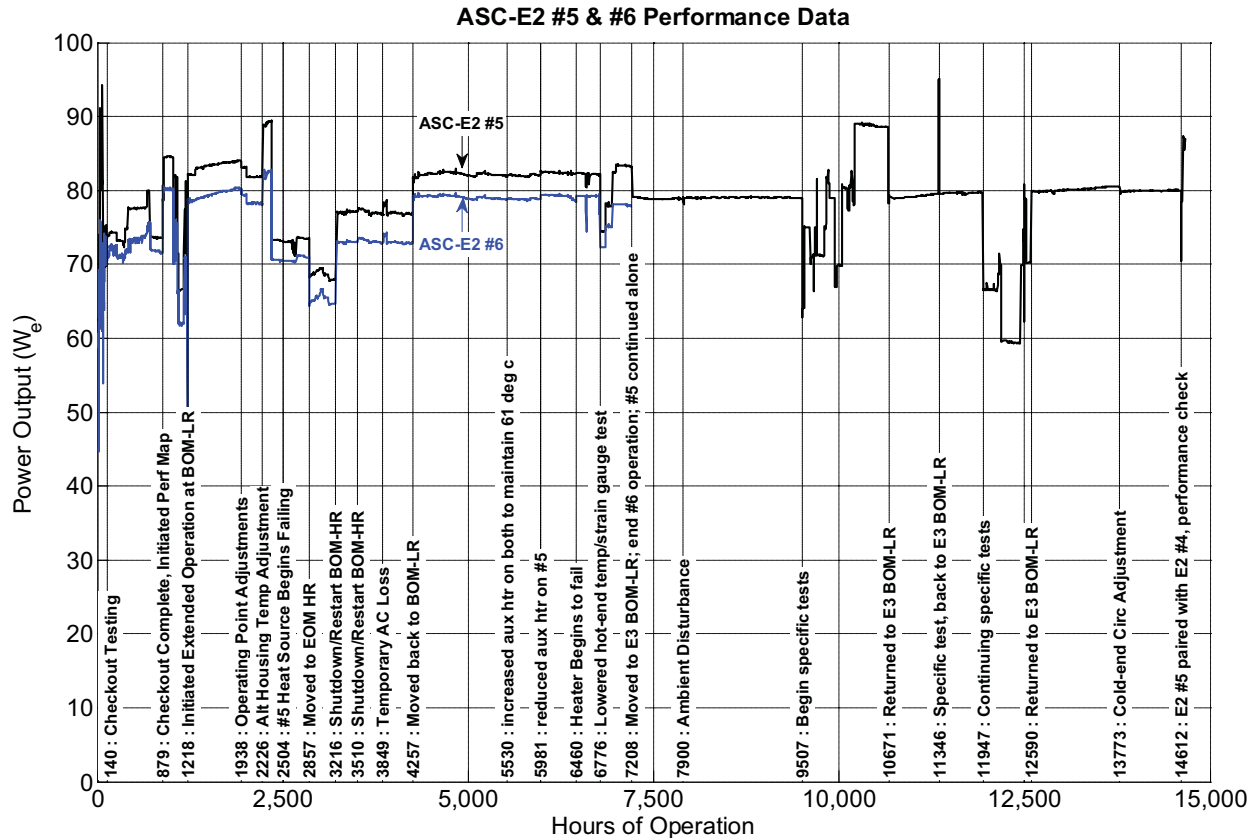


Figure 10.—Advanced Stirling Convertor (ASC)—E2s #5 and #6 performance through 14 650 and 7185 hr of operation, respectively.

## E2 Convertors Removed From Extended Operation

Since 2011, three E2 convertors, #2, #3, and #6, have been removed from operation for inspection. ASC–E2s #2 and #6 operated at Glenn for 2751 and 7184 hr, respectively. Over the operational life of E2 #2, two power variations of ~1 W were observed. Over the operation life of E2 #6, numerous instances of power variations were observed, primarily during the first 1000 hr. During initial performance mapping, slow oscillations in power of ~6 W were observed. After 100 hr of operation, the power variations appeared more like a noisy signal with variations of 1 to 2 W. From 2400 through the remainder of operation life, no more power variations were observed. Because of the differing magnitude and number of performance variations, these two units were selected for inspection. The findings of these inspections have driven corrective actions and other design and process improvements for implementation in the E3s. ASC–E2 #3 operated at Glenn for 841 hr prior to being shipped to Lockheed Martin Coherent Technologies for controller development testing. After review of the data, it was found that ASC–E2 #3 experienced power variations of up to 2 W during performance mapping. Performance mapping occurred early in the operational life of the convertor and no performance variations were observed after performance mapping. During controller development tests, ASC–E2 #3 developed an anomalous sound for which the root cause is unknown. When opened for inspection, ASC–E2 #3 exhibited many of the same symptoms observed in the other E2s for which corrective actions and other design and process improvements had already been developed and implemented for E3s.

## Conclusion

Reliability is a crucial requirement of radioisotope generators for space applications, which are required to have an operational life of 17 years once fueled. NASA Glenn Research Center has been operating Stirling convertors in 24-hr/7-day unattended operation for the purpose of generating a reliability database in support of the Advanced Stirling Radioisotope Generator (ASRG) project. Performance data are continuously recorded, and analyzed to investigate long-term performance trends. To date, Glenn has operated 39 convertors with a cumulative runtime exceeding 530 000 hr. Currently, 11 convertors are operating continuously with the intention of increasing that number when the E3s arrive. Long-term data collected and analyzed to date have indicated steady performance when operating conditions are maintained with exceptions of Advanced Stirling Converter (ASC)–E #1, which experienced a permanent power loss of 7-W<sub>e</sub>, and ASC–E2 #1, which has a known helium leak. Most disruptions to performance have been attributed to variability in support hardware and facility conditions. Power variations observed on the ASC units, both short term and long term, have been investigated and used to drive design and process improvements that will be implemented in future convertors.

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