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# Stirling Convertor Extended Operation Testing and Data Analysis at Glenn Research Center

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## **Abstract**

Extended operation of Stirling converters is essential to the development of radioisotope power systems and their potential use for long-duration missions. To document the reliability of the converters, regular monitoring and analysis of the extended operation data is particularly valuable, allowing us to better understand and quantify long-life characteristics of the converters. Furthermore, investigation and comparison of the extended operation data to baseline performance data provides an opportunity to understand system behavior should any off-nominal performance occur. Glenn Research Center (GRC) has tested 16 Stirling converters under 24-hr unattended extended operation, including four that have operated in a thermal vacuum environment and two that are operating in the Advanced Stirling Radioisotope Generator Engineering Unit. Ten of the sixteen converters are the Advanced Stirling Convertors (ASC) developed by Sunpower, Inc. with GRC. These are highly efficient (conversion efficiency of up to 38 percent for the ASC-1), low-mass converters that have evolved through technologically progressive converter builds. Six converters at GRC are Technology Demonstration Convertors from Infinia Corporation. They have achieved greater than 27 percent conversion efficiency and have accumulated over 185,000 of the total 265,000 hr of extended operation at GRC. This paper presents the extended operation testing and data analysis of free-piston Stirling converters at NASA GRC as well as how these tests have contributed to the Stirling converter's progression toward flight.

## **Introduction**

Extended operation of free-piston Stirling converters at NASA Glenn Research Center (GRC) is fundamental to the development of NASA's next generation of Radioisotope Power Systems (RPS), the Advanced Stirling Radioisotope Generator (ASRG). The ASRG is being developed by Lockheed Martin (LM) under contract to the Department of Energy (DOE). The Advanced Stirling Convertors (ASCs), being developed by Sunpower, Inc. under the management and technical direction of GRC, will be utilized in the ASRG. Various ASC prototypes, as well as two sets of Infinia Corporation Technology Demonstration Convertors (TDCs), are currently under test at GRC's Stirling Research Laboratory. The converters at GRC can be used for either focused tests that are relatively short-term or extended operation tests to establish a reliability database and to examine operating trends over long periods (Ref. 1). 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 of up to 14 years.

Ten of the sixteen converters tested at GRC are from different phases of ASC technology development. Additionally, eight converters of the next phase of technology development, the ASC-E2, will be on extended operation within the next year. To date, Sunpower, Inc. has produced five generations of ASC-related hardware evolving the technology progressively with each build. Estimates for the latest ASC-E2 build indicates power output of 84.5 W<sub>AC</sub> with heat input from the General Purpose Heat Source

(GPHS) to the ASC of 224  $W_{\text{thermal}}$  indicating efficiency of 37.7 percent with a maximum heater head temperature of 850 °C, a reject temperature of 90 °C, and a convertor mass of 1.32 kg (Ref. 2).

This paper provides an update of the Stirling convertor extended operation data to more accurately document their overall reliability after 265,000 hr of combined convertor operation at GRC. To better understand and quantify the long-life characteristics of the convertors advances the technology toward acceptance for flight.

## Nomenclature

ACU	Advanced Stirling Convertor Control Unit
ASC (-E)	Advanced Stirling Convertor (-Engineering Unit)
ASRG (EU)	Advanced Stirling Radioisotope Generator (Engineering Unit)
DOE	Department of Energy
EMI	electromagnetic interference
GPHS	general purpose heat source
GRC	Glenn Research Center
$g_{\text{rms}}$	gravity root mean square
HS	hermetically sealed
LM	Lockheed Martin
RPS	Radioisotope Power System
TDC	Technology Demonstration Convertor
UPS	uninterruptable power supply

## Convertor Operation at Glenn Research Center

Since June 2003, numerous convertors have been operated in GRC’s Stirling Research Laboratory for both short-term tests as well as extended operation. Monitoring and analysis of the performance of this range of convertors is valuable in that the knowledge and experience gained is directly applied to free-piston Stirling convertor development. Table I, updated since its circulation in Reference 3, lists the convertors tested at GRC, as well as convertors that will be tested later this year.

TABLE I.—CURRENT AND UPCOMING CONVERTORS IN EXTENDED OPERATION AT GRC

Convertor	Test environment	Nominal operating temperature (hot/cold), °C	Date operation initiated	GRC hours to date	Status
TDC #13 and #14	In air	650/80	June 2003	47,200	Ongoing test
TDC #5 and #6	Thermal vacuum	630/70	Nov. 2004	10,543 and 10,382	Completed test
TDC #15 and #16	In air	650/80	Mar. 2005	33,400	Ongoing test
ASC-0 #1 and #2	In air and thermal vacuum	645/72	Feb. 2007	15,363	Ongoing test
ASC-0 #3 and #4	In air and launch simulation	650/90	Aug. 2007	12,700	Ongoing test
ASC-1 #3 and #4	In air	850/90	May 2007	1,817	EMI testing
ASC-1HS #1 and #2	In air and launch simulation	850/90	Feb. 2008	2,823 and 4,106	Ongoing test
ASC-E #2 and #3	In air and environmental	625/70	Nov. 2008	4,900	Ongoing test
ASC-E #1 and #4	In air and launch simulation	650/90	2009	53 and 0	Future test
ASC-E2 #1 to #8	In air and launch simulation		2009		Future test

## Extended Operation Results to Date

### Advanced Stirling Radioisotope Generator Engineering Unit (ASRG EU)

The ASRG EU was designed and fabricated by LM under contract to the DOE. It contains two convertors; ASC-E #2 is the outboard convertor located farthest from the mounting end in the A position and ASC-E #3 is located in the B position at the inboard end. The controller is mounted to the outside of the housing.

After fabrication, the ASRG EU completed a variety of tests at the LM facility, including thermal performance in a vacuum chamber, mechanical disturbance, sine transient, random vibration, shock, and electromagnetic interference (EMI) (Ref. 4). Upon conclusion of these tests, the ASRG EU underwent an internal inspection. The electric heat sources, which were dynamically and dimensionally equivalent to a GPHS module, were replaced with a cartridge heater design furnished by GRC. These heaters are expected to have the higher reliability required for extended operation testing. The ASRG EU was operated for a total of 1,124 hr at LM before shipping to GRC.

The ASRG EU was delivered to GRC on August 28, 2008. A special test facility was designed and fabricated to operate the vertically oriented ASRG EU under controlled conditions (Refs. 5 and 6). Figure 1 shows the ASRG EU test station. The ASRG EU was initially operated under AC bus control to characterize performance of the engineering unit and the test facility independent of the Advanced Stirling Convertor Control Unit (or ACU). Instrumentation is used to monitor various parameters including temperatures throughout the ASRG EU and the test facility, heat input, power output, mounting interface forces, and other parameters. Extended operation commenced on November 6, 2008. The ASRG EU has been operated at a hot-end temperature of 625 °C on both convertors, while the rejection temperature varied to nominally 69 °C on ASC-E #2 and 66 °C on ASC-E #3. The heat rejection is accomplished by cooled air flowing over the unit from the ASC B end to the ASC A end. Since the heat rejection from the two convertors is not independently controlled, and the cooled air reaches the ASC B end first, the ASC-E #3 cold-end temperature has been slightly lower than the ASC-E #2 cold-end temperature.



Figure 1.—ASRG EU test station. ASRG EU in an enclosure on test stand inside the ASRG EU and ASC-E #1 and #4 special test facility.

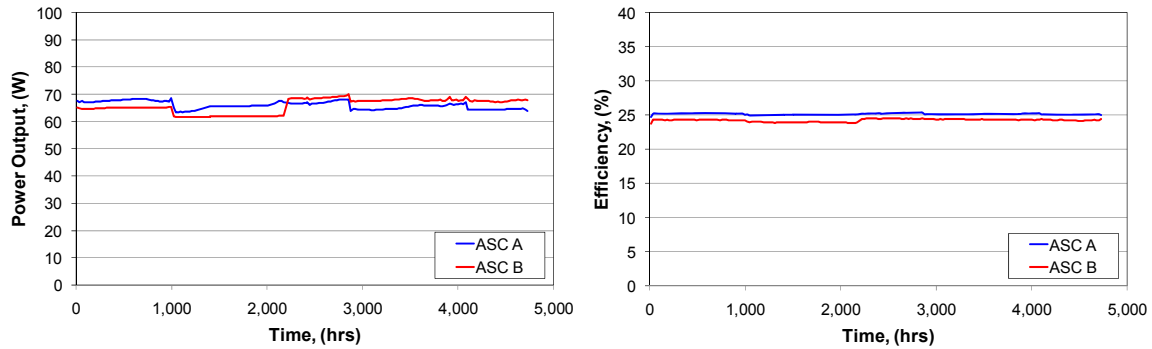


Figure 2.—Power output and efficiency performance data from ASRG EU through 4,900 hr of operation.

A comparison was made of ASRG EU alternator power as measured at LM versus power measured at GRC. The alternator power measurements were comparable within  $\pm 1.5$  W.

Changes in piston amplitude occurred during operation because of test rack impedance variation as well as operating setpoint adjustments. The piston amplitude fluctuated between 4.10 and 4.30 mm on ASC-E #2 and 4.00 and 4.39 mm on ASC-E #3. These operating setpoint adjustments, reflected in the performance graphs of Figure 2, were made in response to the piston amplitude increases caused by the impedance variations. Setpoint adjustments to decrease AC bus voltage, and thus piston amplitude and power, were made at 1,003 and 2,874 hr of operation. Milliohm-level increases in test rack impedance essentially resulted in a change in the operating point, affecting the piston amplitude and output power. These changes can be seen in Figure 2.

A number of upgrades were made to the test rack after 2,197 hr of operation with the intent of reducing the variations in impedance. These included seating capacitor connections in a more robust fashion, soldering some connections, and improving other connections. Subsequent tests showed that power variation was reduced, especially on the ASC A side of the test rack. The abnormally high ASC A-side impedance was reduced to be comparable to ASC B-side impedance, resulting in ASC-E #3's power now slightly above that of ASC-E #2. The data also showed that variation was not eliminated, especially on the ASC B side, so further improvements to the test rack are under way.

The ASRG EU has operated to date with no measurable change in convertor performance. As shown in Figure 2, overall performance data for these convertors shows stable operation (with exception of manual adjustments). The ASRG EU has achieved over 4,900 hr of extended operation and will operate on ACU control in August 2009.

### ASC-1 HS #1 and #2

Upon arrival to GRC in November 2007, the ASC-1 HS #1 and #2, which are hermetically sealed units with the exception of the helium fill tube, underwent heater head diameter measurements, thermocouple instrumentation, and vacuum bakeout before beginning extended operation in March 2008. These units can reach temperatures up to 850 °C with a MarM-247 heater head that allows for higher hot-end temperatures. Within 8 hr of initiating 850 °C operation, a power anomaly occurred causing a hot-end temperature transient to trigger a shutdown of the convertors. To help minimize this type of shutdown incident, the temperature limits were adjusted to provide greater margin for tolerating short-term transients. Data from this initial run showed the anomalies were in the form of rapid and spontaneous power output spikes of approximately 1 W above nominal and occurred roughly every 2 hr.

Convertor operation moved forward but at lower operating conditions of 750 and 650 °C hot-end temperatures. Data from these lower temperature runs showed that power variations were occurring, but were slightly under the threshold to trigger a shutdown since the temperature limits were previously adjusted. Operation at 750 °C resulted in anomalous spikes on the order of approximately 2 W every 8 hr, and 650 °C operation resulted in anomalous spikes of approximately 1 W every 24 hr. No obvious



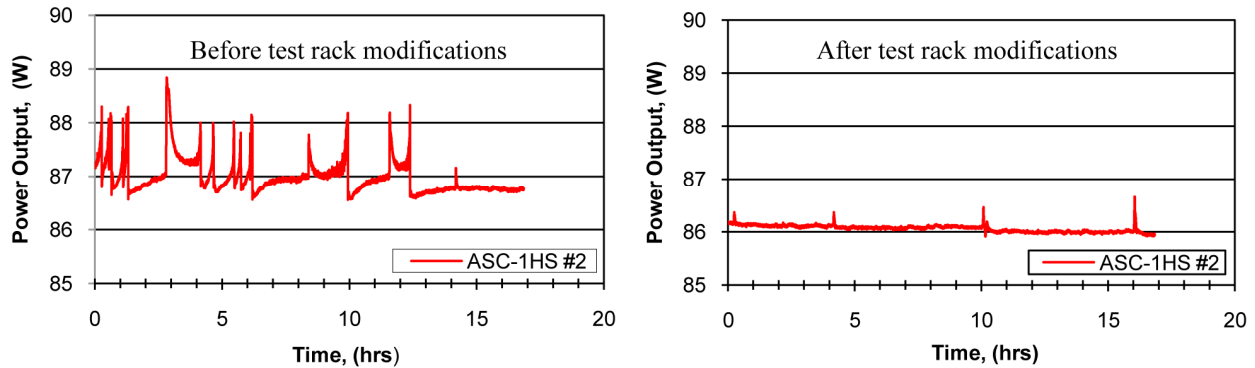


Figure 3.—ASC-1 HS #1 and #2 power anomalies before and after test rack modifications.

reasons were found for the anomalies, so an investigation was initiated to find the root cause. The converters were operated at various operating temperatures in both dual-opposed and single configuration as well as horizontal and vertical orientation. Different alternator output connections and varying AC bus controller resistances were employed, and although the characteristics of the anomalies varied, the behavior remained. Additionally, the power anomalies appeared in both converters, but generally occurred independent of each other.

The investigation was then directed to the test rack, where a visual inspection of all components and wiring was performed. Furthermore, the AC power supply in the AC bus controller was used as a power source, and a resistive load was used in place of the converters. The power variations were still present utilizing the resistive load, indicating that the test rack was responsible for the anomalies, and not the converters. Further troubleshooting focused the suspected problem to the test rack's load panel, and changes were made to the load panel based on these findings. These modifications included replacing the wire nuts on the transformer leads with solder joints, repairing a poor solder joint that was found in the alternator power path, and removing a relay in the power circuit. The output relay was originally installed to allow the test operator to switch between the AC bus controller and a Zener-diode controller. However, only AC bus control is now used, making the output relay unnecessary in this test rack. Although the modifications did not completely eliminate the power variations, analysis of the 2-sec power performance data (as shown in Fig. 3) indicated a fairly significant improvement in stability of the convertor operating point.

ASC-1 HS #1 and #2 operation continued throughout the power anomaly investigation, accumulating nearly 3,000 hr of operation on ASC-1 HS #1 and 4,200 hr on ASC-1 HS #2, with an extensive amount of operation at the relatively higher hot-end temperature of 750 °C. Currently, new high-temperature-capable heat sources are under evaluation at GRC that will allow long-term, reliable operation at 850 °C, and the anomaly investigation is progressing.

### ASC-1 #3 and #4

Extended operation of the ASC-1 #3 and #4 was ceased after nearly 1,800 hr at GRC in December 2007. ASC-1 #3 and #4 were not operated during 2008, but were sent back to Sunpower, Inc. after the displacer epoxy joint failed due to an over-temperature condition encountered during an insulation loss test (as described in Ref. 3).

Originally designed only for developmental activities rather than long-life testing, these converters included multiple o-ring seals at the flange joints and pressure vessel ports. During Sunpower's, Inc. inspection of the converters following extended operation at GRC, it was found that oxygen had permeated through the o-ring seals causing damage to some internal components. Based on this finding, a new pressure vessel was designed to eliminate the o-rings exposed to atmosphere at the aft end to potentially decrease oxygen permeation. This new design required three changes to the pressure vessel; the alternator power feedthrough was changed to a welded, hermetic feedthrough, the fast linear displacement transducer (FLDT) was changed from a mount with an o-ring to a welded style, and the

helium fill port was changed from an o-ring seal port to a brazed tube with a welded metal gland-face seal fitting. The main pressure vessel and heater head o-rings remained, and as during earlier operation at GRC, will be enclosed in an argon environment intended to eliminate the presence of oxygen. Because the new welded alternator feedthrough is located on the aft end of the pressure vessel, the pressure vessel must be made from two sections: a main cylinder portion and a cap. The cylinder will be placed around the alternator, the alternator wires will be soldered to the feedthrough in the cap, and the cap will be welded to the cylinder. After welding, disassembly of the two main sections would be accomplished by cutting off the cap.

A second pressure vessel was designed and fabricated for use on the ASC-1 #3 and #4 during EMI testing. These test pressure vessels were made from Carpenter High Permeability Perm-49 to mitigate the AC magnetic emissions from the alternator. In April 2009, ASC-1 #3 and #4 completed baseline performance testing at Sunpower Inc., with the Perm-49 pressure vessels before returning to GRC. The convertors underwent EMI testing in June 2009 to characterize the emitted AC magnetic field strength.

Following EMI testing, the convertors were returned to Sunpower Inc., where the Perm-49 pressure vessels will be replaced with the new pressure vessels. The combination of the argon environment surrounding the heater head and pressure vessel o-rings, coupled with the elimination of o-rings from the aft end of the pressure vessel is to enable extended operation without complications caused by internal component oxidation. Four candidate high-temperature heat sources are currently being evaluated at GRC for the higher heater head temperatures required for ASC-1 #3 and #4. The heat sources maintain 950 to 1000 °C temperatures to make use of the MarM-247 heater head for operation up to 850 °C. Extended operation will resume at GRC at full design conditions in September 2009.

### **ASC-0 #1 and #2**

NASA GRC has been operating several ASCs in support of the ASRG project, however, the first ASCs to be operated at GRC were ASC-0 #1 and #2, which include Inconel 718 heater heads and hermetically sealed flange joints. Delivery of the convertors was in December 2006, and in-air operation began in February 2007, where they operated at their nominal design conditions for approximately 600 hr. These operating conditions included 650 °C hot-end temperature, 90 °C rejection temperature, and 4.50-mm piston amplitude. Following in-air operation, they were reconfigured for thermal vacuum operation. Convertor operation in a thermal vacuum environment was initiated in March 2007 and concluded in January 2009, accumulating 15,363 hr of in-air and thermal vacuum operation. The majority of operation in thermal vacuum was at less-than-design piston amplitude because of questionable instrumentation or convertor behavior, but other parameters, such as hot-end temperature, were maintained at the nominal design value. Several periods of nonsteady performance were observed throughout in-air and thermal vacuum operation and are described in Reference 3. The thermal vacuum test of ASC-0 #1 and #2 was concluded in January 2009 to conduct an inspection of the convertors at Sunpower Inc. cursory assessment of the convertors at GRC upon removal from thermal vacuum revealed all hardware to be intact with the minor exception of fractured ceramic washers on the electrical heater leads. The convertors were returned to Sunpower Inc. for inspection, where they will be refurbished if necessary and returned to GRC in September 2009.

### **ASC-0 #3 and #4**

The ASC-0 #3 and #4 units, designed similar to the ASC-0 #1 and #2 units with Inconel 718 heater heads and hermetically sealed flange joints, began operation at GRC in August 2007. Their nominal design conditions are equivalent to the ASC-0 #1 and #2 at 650 °C hot-end temperature, 90 °C rejection temperature, and 4.50-mm piston amplitude. Continuous operation of these convertors was halted in August 2008, with over 7,400 hr of operation, to prepare them for flight-acceptance-level and launch

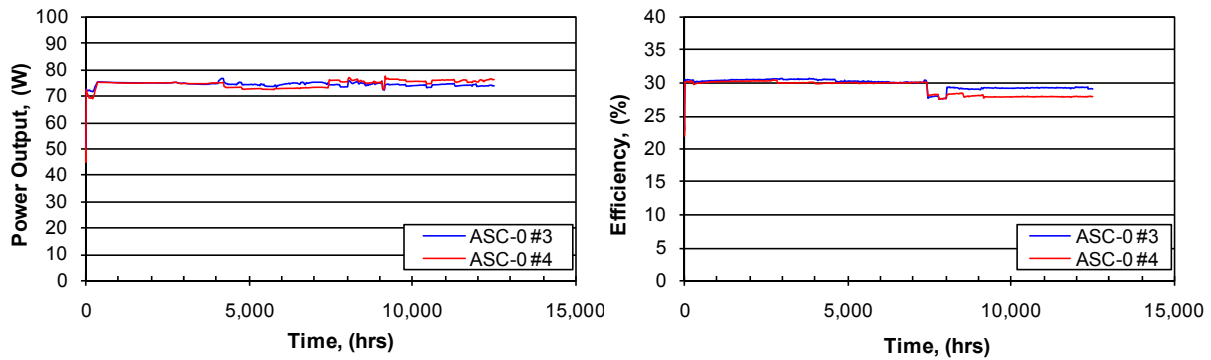


Figure 4.—Power output and efficiency performance data from ASC-0 #3 and #4 through 12,700 hr of operation.

simulation vibration testing in three orthogonal axes at GRC’s Structural Dynamics Laboratory. The intent of the test was to subject the converters to the same environmental conditions as flight converters, which would experience a workmanship vibration test during manufacturing, acceptance vibration test when the generator is fueled, and launch vibration. ASC-0 #3 was subjected to acceptance and launch simulation levels of 8.7 g root mean square ( $g_{rms}$ ) in all three axes using the standard RPS specification flight acceptance profile (Ref. 7). With data from that vibration test and the response measured by LM when they tested the ASRG EU, the vibration profile was adjusted to simulate the dynamic conditions imposed on converters installed in the ASRG EU. This resulted in a test level for ASC-0 #4 of 8.4  $g_{rms}$  in the two lateral axes, and 14.3  $g_{rms}$  in the axial direction as measured at the pressure vessel.

Furthermore, ASC-0 #3 and #4 underwent heater head diameter measurements by the Structures and Materials Division at GRC. A previously developed methodology was applied to measure the converter heater head using a laser micrometer scanning technique and a National Instruments data acquisition system to record analog diameter versus axial position. The laser scanning technique and the configured data acquisition system were utilized to perform heater head diameter versus axial length measurements at 45° circumferential intervals. The purpose of the activity was to provide baseline data for comparison of future heater head measurement data subsequent to GRC in-house testing, providing a means to track creep of the heater head assembly should creep strains accumulate throughout extended operation testing. The computed creep strains will be used subsequently in the heater head’s life assessment.

Anomalous behavior similar to what was discussed previously with ASC-1 HS data but of lesser magnitude also occurred on ASC-0 #3 and #4. As with the ASC-1 HS #1 and #2, power anomalies would appear in both converters, but would generally be independent of each other. Poor connections and a malfunctioning relay appeared to be the root cause of the anomalies. The relays were removed from the power circuit since they were no longer needed, and the faulty connections were soldered. As shown in Figure 4, overall performance data for these converters shows steady operation (with exception of manual adjustments) and no measurable change in performance after achieving over 12,700 hr of extended operation.

### TDC #13 and #14

TDC #13 and #14 are the longest running pair of Stirling converters at GRC, with over 47,200 hr (5.4 years) of operation. Extended operation of these converters began in June 2003. Using TDC #13 and #14 as a benchmark for extended operation testing and applying the knowledge gained from these converters to other test articles at GRC has directly resulted in greater overall uptime for all converters in the Stirling Research Laboratory. Test facility upgrades such as improved failsafe protection circuit designs to eliminate false trips as well as test facility maintenance schedules are credited to experience gained from the operation of these long-running converters. Ongoing test facility maintenance includes cleaning, replacement, or calibration of the cooling plumbing and pumps, heaters, rack electronics,

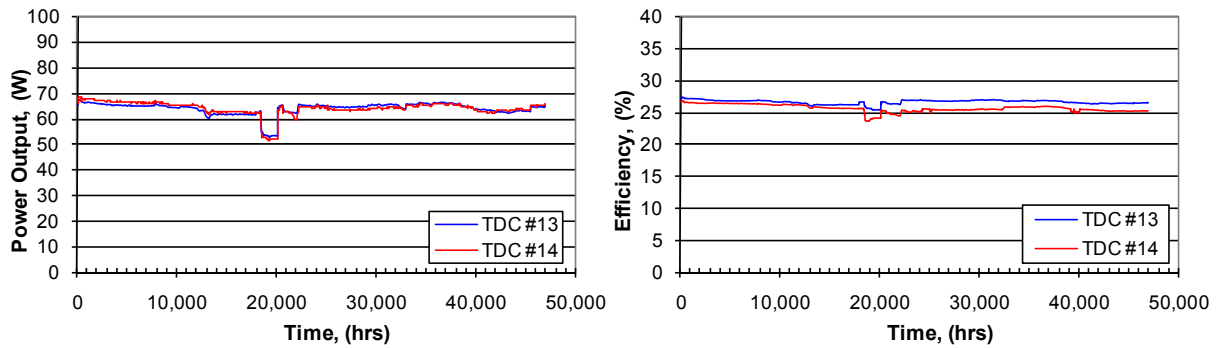


Figure 5.—Power output and efficiency performance data from TDC #13 and #14 through 47,200 hr of operation.

sensors, building heating, ventilating, and air conditioning (HVAC), working gas management system, and the gas analysis system. To address the possibility of facility power loss, uninterruptable power supplies (UPS) provide backup power to each test station in the Stirling Research Laboratory. In the event of a facility power outage, the UPS at each test station is connected and a signal is sent to the LabVIEW system. The LabVIEW system monitors the outage, and if it extends beyond 5 min, the LabVIEW system initiates a controlled shutdown. The UPS system can also maintain operation for up to 30 min to perform maintenance on the facility electrical system without needing to shut down the convertors (Ref. 3). A 50-kW generator provides backup power in the event of an extended facility power outage.

TDC #13 and #14 were partially disassembled and inspected after 18,400 hr of operation. The inspection, performed by GRC and observed by Infinia Corporation, consisted of pressure vessel removal and resulted in no identified changes in condition since assembly. After 19,100 hr of operation, the o-ring seal flanges were hermetically sealed at Edison Welding Institute, but the helium fill tubes remain connected to the gas management system to allow for analysis of the working fluid throughout extended operation. A more detailed description of the operation through 38,400 hr can be found in References 1, 8, and 9.

Figure 5 shows output power and net efficiency to date for TDC #13 and #14. The slight degradation in power and efficiency prior to 19,000 hr is attributed to regenerator oxidation caused by oxygen permeation through the o-ring seals. Hermetically sealing the flanges at 19,100 hr prevented further oxidation. After hermetic sealing, the convertors were operated at a lower power level until 20,000 hr, at which time they underwent vacuum bakeout to prepare for full power operation. Shortly after returning to full power operation, the cartridge heaters began to degrade and the power level was again decreased, resulting in heater replacement on both convertors at 22,000 hr of operation. The heaters have currently been operating at full power for over 23,000 hr, during which time they have experienced seven thermal cycles to room temperature. At approximately 38,000 hr of convertor operation, power output decreased because of a decline in average heater temperature resulting from aging cartridge heaters as well as drift in the Zener-diode controller. Due to this change in operating point, the temperature and controller load were subsequently adjusted back to the original operating point, and convertor power output returned to expected levels. TDC #13 and #14 have continued to operate with negligible change in performance since the cartridge heater change at 22,000 hr and remain on extended operation testing as an integral part of GRC's development of long-life radioisotope power systems.

### TDC #15 and #16

TDC #15 and #16 are the second longest running pair of Stirling convertors at GRC, with over 33,400 hr (3.8 years) of operation. Extended operation of these convertors began in March 2005. The o-ring seal flanges were hermetically sealed on these convertors at Edison Welding Institute after 4,200 hr of operation, and as with the first set of TDCs, the helium fill tubes remain connected to the gas management system to allow for analysis of the working gas throughout extended operation. A more detailed description of the operation through 24,600 hr can be found in References 3 and 9.

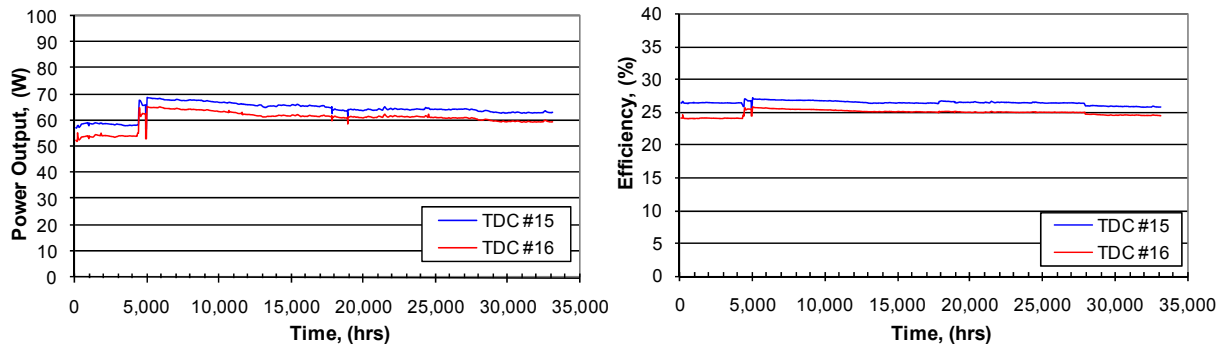


Figure 6.—Power output and efficiency performance data from TDC #15 and #16 through 33,400 hr of operation.

Figure 6 shows output power and net efficiency to date for TDCs #15 and #16. Prior to hermetic sealing, the converters operated at a reduced hot-end temperature to help prevent internal oxidation. After hermetic sealing, the converters were operated at a lower power level for about 100 hr before undergoing vacuum bakeout. They returned to full temperature operation at 4,400 hr. As with the first set of converters following hermetic sealing, the cartridge heaters on TDC #15 and #16 also began to degrade after returning to full temperature operation, resulting in heater replacement on both converters at 4,900 hr of operation. The heaters have currently been operating at full power for over 27,000 hr, during which time they have experienced eleven thermal cycles to room temperature. TDC #15 and #16 have continued to operate with negligible change in performance since the cartridge heater change at 4,900 hr and remain on extended operation testing as an integral part of GRC's development of long-life radioisotope power systems.

#### ASC-E #1 and #4

ASC-E #1 and #4 units, delivered to GRC in December 2008 and May 2009, respectively, are being prepared for extended operation testing at GRC's Stirling Research Laboratory. The ASC-E #1 is the spare convertor from the fabrication of the ASRG EU, and the ASC-E #4 was built using high-value spare parts from the earlier ASC-E builds including the heater head and cold-side adapter flange. These converters utilize Inconel 718 heater heads and therefore operate at a maximum hot-end temperature of 650 °C and a rejection temperature of 40 to 90 °C. The units have been hermetically sealed by welding the flange joints, and the fill tube has been pinched off. Shortly after their arrivals at GRC, ASC-E #1 and #4 underwent heater head diameter measurements with the Structures and Materials Division.

Vibration testing was successfully completed at GRC's Structural Dynamics Laboratory on ASC-E #1 with the ACU in February 2009. As part of an extended life testing program combined with a test plan to validate software and test configuration changes, the ACU operated the ASC-E at launch conditions while the convertor was exposed to qualification-level vibration in the axial direction and flight-acceptance-level vibration in the lateral axes. The convertor, shown in Figure 7, operated at approximate launch conditions of 625 °C hot-end temperature, 60 °C rejection temperature, and 4.25-mm piston amplitude throughout the test. Comparison of operational characteristics of the units prior to and after vibration testing further confirmed the integrity of the hardware. The test represents the first operation of a Stirling convertor under control of the ACU at GRC. ASC-E #1 operated at expected launch conditions during all vibration testing. ASC-E #4, which was motored during vibration, successfully passed workmanship-level vibration testing in all three axes at GRC's Structural Dynamics Laboratory in April 2009. Structural integrity was confirmed by comparison of sine sweeps conducted prior to and after exposure to workmanship random vibration. ASC-E #1 and #4 will be in extended operation at GRC in August 2009.



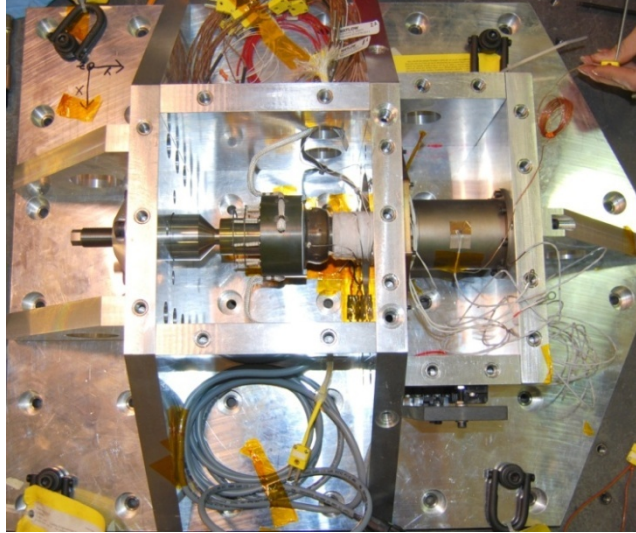


Figure 7.—ASC-E in mounting fixture for vibration testing at GRC.

## Conclusions

Stirling convertors have been operated for a total of more than 265,000 hr in GRC's Stirling Research Laboratory and have completed various specialized tests to help refine the hardware and test stations. Monitoring and analysis of the performance of this range of convertors, in both air and thermal vacuum environments, is valuable in that the knowledge and experience gained is directly applied to the advancement of free-piston Stirling convertor development. As currently planned, the present build, designated the ASC-E2, will be on extended operation testing at GRC within the next year. The subsequent phase of technology development, the ASC-E3 convertor, will be designed with a focus on refining the manufacturing processes (Ref. 10). GRC's contribution of convertor testing and analysis is critical to the development and application of the next generation of practical radioisotope power applications, the ASRG Qualification Unit.

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<b>13. SUPPLEMENTARY NOTES</b>					
<b>14. ABSTRACT</b> Extended operation of Stirling convertors is essential to the development of radioisotope power systems and their potential use for long-duration missions. To document the reliability of the convertors, regular monitoring and analysis of the extended operation data is particularly valuable, allowing us to better understand and quantify long-life characteristics of the convertors. Furthermore, investigation and comparison of the extended operation data to baseline performance data provides an opportunity to understand system behavior should any off-nominal performance occur. Glenn Research Center (GRC) has tested 16 Stirling convertors under 24-hr unattended extended operation, including four that have operated in a thermal vacuum environment and two that are operating in the Advanced Stirling Radioisotope Generator Engineering Unit. Ten of the sixteen convertors are the Advanced Stirling Convertors (ASC) developed by Sunpower, Inc. with GRC. These are highly efficient (conversion efficiency of up to 38 percent for the ASC-1), low-mass convertors that have evolved through technologically progressive convertor builds. Six convertors at GRC are Technology Demonstration Convertors from Infinia Corporation. They have achieved greater than 27 percent conversion efficiency and have accumulated over 185,000 of the total 265,000 hr of extended operation at GRC. This paper presents the extended operation testing and data analysis of free-piston Stirling convertors at NASA GRC as well as how these tests have contributed to the Stirling convertor's progression toward flight.					
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