



Extended Operation of Stirling Convertors at NASA Glenn Research Center

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Abstract

NASA Glenn Research Center (GRC) has been supporting development of free-piston Stirling conversion technology for spaceflight electrical power generation since 1999. GRC has also been supporting the development of the Advanced Stirling Radioisotope Generator (ASRG) since 2006. A key element of the ASRG project is providing life, reliability, and performance data for the Advanced Stirling Convertor (ASC). The Thermal Energy Conversion branch at GRC is conducting extended operation of several free-piston Stirling convertors. The goal of this effort is to generate long-term performance data (tens of thousands of hours) on multiple units to build a life and reliability database. Currently, GRC is operating 18 convertors. This hardware set includes Technology Demonstration Convertors (TDCs) from Infinia Corporation, of which one pair (TDCs #13 and #14) has accumulated over 60,000 hr (6.8 years) of operation. Also under test are various Sunpower, Inc. convertors that were fabricated during the ASC development activity, including ASC-0, ASC-E (including those in the ASRG engineering unit), and ASC-E2. The ASC-E2s also completed, or are in progress of completing workmanship vibration testing, performance mapping, and extended operation. Two ASC-E2 units will also be used for durability testing, during which components will be stressed to levels above nominal mission usage. Extended operation data analyses from these tests are covered in this paper.

Nomenclature

ASC	Advanced Stirling Convertor
ASRG	Advanced Stirling Radioisotope Generator
BOM	beginning of mission
DOE	Department of Energy
EOM	end of mission
EMI	electromagnetic interference
GRC	Glenn Research Center
GPHS	General Purpose Heat Source
LMCT	Lockheed Martin Coherent Technologies
LMSS	Lockheed Martin Space Systems
LR	low rejection
HR	high rejection
SRG-110	Stirling Radioisotope Generator, 110-W _e
TDC	Technology Demonstration Convertor

1.0 Introduction

The Thermal Energy Conversion branch at the NASA Glenn Research Center (GRC) has been supporting the development of free-piston Stirling conversion technology for space electrical power since 1999 (Ref. 1). Free-piston Stirling conversion offers a thermal-to-electric conversion efficiency of greater than 25 percent at the system level, which is a factor of four greater than thermoelectric conversion. Thermoelectric-conversion radioisotope power systems have been used in space since 1961, most notably on the Apollo missions, the Voyager planetary probes, and soon the Mars Science Laboratory (Ref. 5). The higher conversion efficiency offered by free-piston Stirling technology reduces the required amount of radioisotope fuel for a given power output. Between 2001 and 2006, Lockheed Martin Space Systems (LMSS) was contracted as system integrator by the Department of Energy (DOE) to design a 110-W_e, Pu-238-fueled Stirling-conversion generator. This design, designated the Stirling Radioisotope Generator-110 (SRG-110), comprised two Infinia, Corporation free-piston Stirling convertors, each receiving heat from one General Purpose Heat Source (GPHS) module. During this time period, NASA GRC began continuous, extended operation of several Infinia, Corporation Technology Demonstration Convertors (TDCs) (Ref. 1). The TDCs were fabricated during technology development activities preceding the SRG-110 project, but are functionally the same as those of the SRG-110 design. In 2006, the project was redirected to use Sunpower, Inc. Advanced Stirling Convertor (ASC) technology in lieu of Infinia technology to increase the hot-end conversion temperature. This offered increases in the generator's specific power and overall conversion efficiency. As such, the generator was renamed the Advanced Stirling Radioisotope Generator (ASRG). Recently, NASA has announced three candidate Discovery 12 missions, two of which would make use of the ASRG (Ref. 6).

At the time of the redirection towards ASRG, GRC also began continuous, extended operation of several ASCs. Since dynamic energy conversion has yet to be used for a spaceflight application, demonstration of the technology's reliability is paramount to the progression of Stirling technology to flight. The GRC convertor level testing serves the function of building a reliability database to support the capability of Stirling convertors for spaceflight applications. Continuous extended convertor operation provides performance data over a sufficient length of time to observe long-term trends (tens of thousands of hours). Initial Stirling-conversion radioisotope power system development envisioned missions to the outer planets, with cruise times on the order of 17 years. It is time-prohibitive to operate any single unit for 17 years, and there is no feasible method for accelerating life testing at the convertor level. Therefore, the tactic employed is to operate many units to accumulate convertor hours of operation useful for supporting reliability analyses.

A total of 38 free-piston Stirling convertors have been operated at GRC in support of dynamic energy conversion for a radioisotope power system (Refs. 2 and 3), with a cumulative runtime exceeding 400,000 hr. GRC is currently maintaining 24/7 operation of 18 convertors, for which the cumulative runtime exceeds 350,000 hr. Four of these are Infinia TDCs, while the remainder are Sunpower ASCs from various points along the ASC technology development path. A summary of the ongoing tests is shown in Table I. An example extended operation test station with two ASC-E2s is shown in Figure 1. Details of test station design and operation have been discussed previously in References 1 to 4. The Infinia convertors were the first to begin extended operation, and have the most runtime. The leader in runtime is the TDC #13 and #14 pair, which have each operated for over 60,000 hr (~6.8 years). GRC began operating ASCs in 2007, shortly after the project was redirected to use Sunpower's convertor design. Three ASC designs are currently being operated: ASC-0, ASC-E, and ASC-E2. The ASC-0 design was the first to implement hermetic sealing of the convertor's pressure joints. Later, ASC-E units arrived, which incorporated design modifications specific to LMSS's ASRG engineering unit (ASRG-EU). Two ASC-Es (#2 and #3) were assembled into the ASRG-EU by LMSS, which was subsequently

delivered to GRC for extended operation and controller testing (Ref. 4). In parallel with the first pair of ASC-Es, a second pair (ASC-E #1 and #4) was fabricated and delivered to GRC. These were not integrated into a generator, but were assembled into a test station by GRC that aesthetically resembles the ASRG-EU. The ASC-E2 design is capable of higher hot-end temperature operation. Eight ASC-E2 units were delivered to GRC throughout 2010 and are at various stages in the standard test sequence (Ref. 2).

TABLE I.—SUMMARY OF ON-GOING STIRLING CONVERTOR OPERATION AT NASA GRC AS OF JULY 1, 2011

Convertors	Supplier	Nominal operating temperatures (Hot/Cold, °C)	Nominal per-convertor power output (W_e)	Date initiated	Per-convertor runtime (hrs)
TDC #13 & #14	Infinia Corp.	650/80	65	Jun 2003	60,000
TDC #15 & #16		650/80	65	Mar 2005	49,000
ASC-0 #3 & #4	Sunpower Inc.	650/90	75	Aug 2007	25,000
ASC-E #2 & #3 (ASRG-EU)		625/70	65	Nov 2008	19,000
ASC-E #1 & #4		650/70	65	Dec 2009	10,000
ASC-E2 #1		850/50	80	Mar 2010	6,200
ASC-E2 #2				Feb 2010	2,700
ASC-E2 #3 & #4				Aug 2010	800
ASC-E2 #5 & #6				Aug 2010	4,800
ASC-E2 #7				Nov 2010	2,100
ASC-E2 #8	Jun 2011			20	

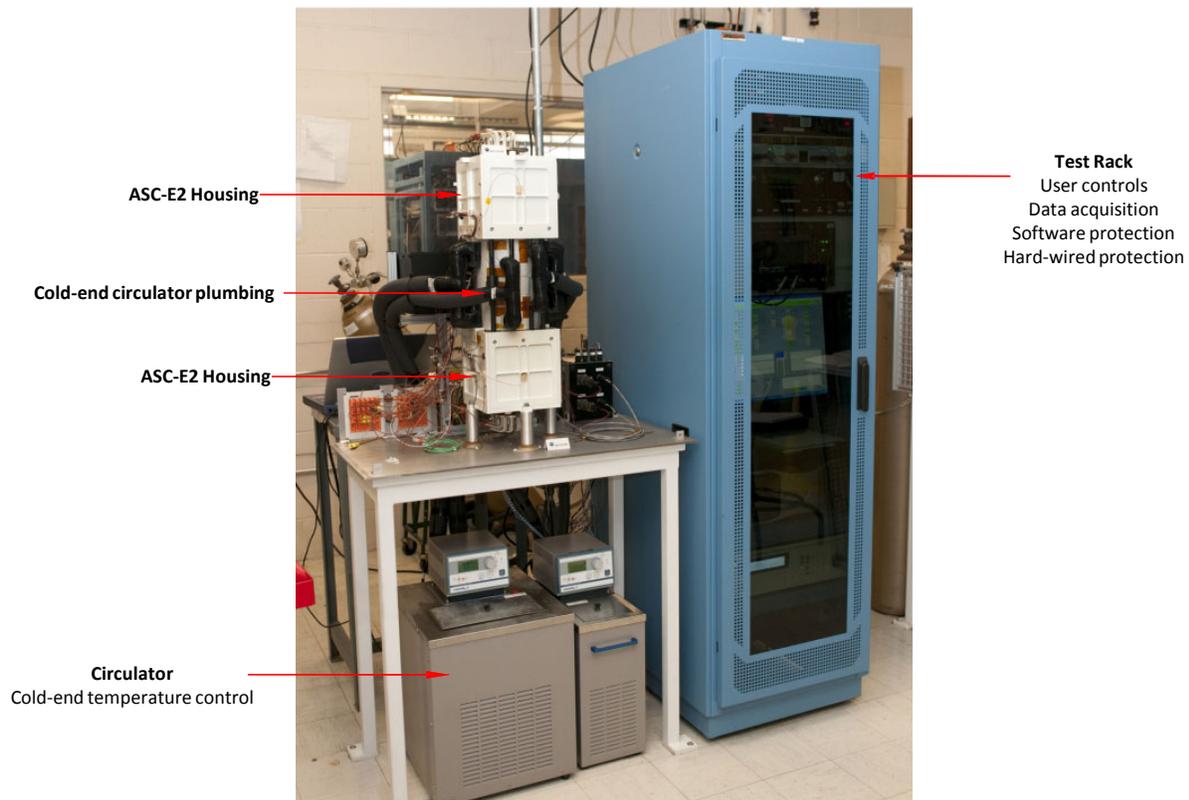


Figure 1.—Example ASC-E2 extended operation test station at NASA GRC.

2.0 Extended Operation Test Results

2.1 TDCs #13 and #14

TDC #13 and #14 is the longest-running pair of Stirling convertors at GRC, with 60,000 hr each. Operation of these units has been discussed previously by References 1 and 3. These units produce 65 W_e at a hot-end temperature of 650 °C and a cold-end temperature of 80 °C. Inconel 718 was chosen for the heater head material due to both its high-temperature capability and the ample available tertiary creep data (Ref. 1). This was important because at the time, no other candidate material had available tertiary creep data necessary to design a long-life heater head. The convertors have operated without failure, and all observed degradation has been attributed to sources other than the workings of the device. Shutdowns have been required only to address support facility issues. The continued operation of these units has demonstrated the viability of dynamic power conversion for space power. The data show that dynamic conversion can attain the long-life necessary for spaceflight applications by eliminating mechanical wear mechanisms via non-contacting moving components. The data also show that the non-moving components can be designed to attain long life, such as the heater head material at high-temperature and stress.

These convertors began extended operation in June 2003. A plot of the convertor performance data is shown in Figure 2. Initially, the pressure joints were sealed only with o-rings. This was shown to allow inward permeation of air despite the existence of high-pressure helium gas inside the convertor. The permeation of oxygen into the helium working gas resulted in oxidation of the regenerator material, which caused the decline in convertor performance shown during the first 18,000 hr of operation. Beginning at approximately 18,000 hr, the convertors were operated at reduced hot-end temperature in anticipation of welding the pressure joints. At 19,000 hr, the pressure joints were welded, effecting a hermetic seal at these joints, but the helium fill line remained to enable working gas sampling and mean charge pressure adjustment. The convertors were then operated at reduced hot-end temperature until approximately 20,000 hr, after which operation resumed at full temperature. Since sealing the joints and eliminating permeation through the o-rings, the initially-observed degradation was eliminated. The performance became more steady after the sealing process. There were subsequent disturbances in the performance

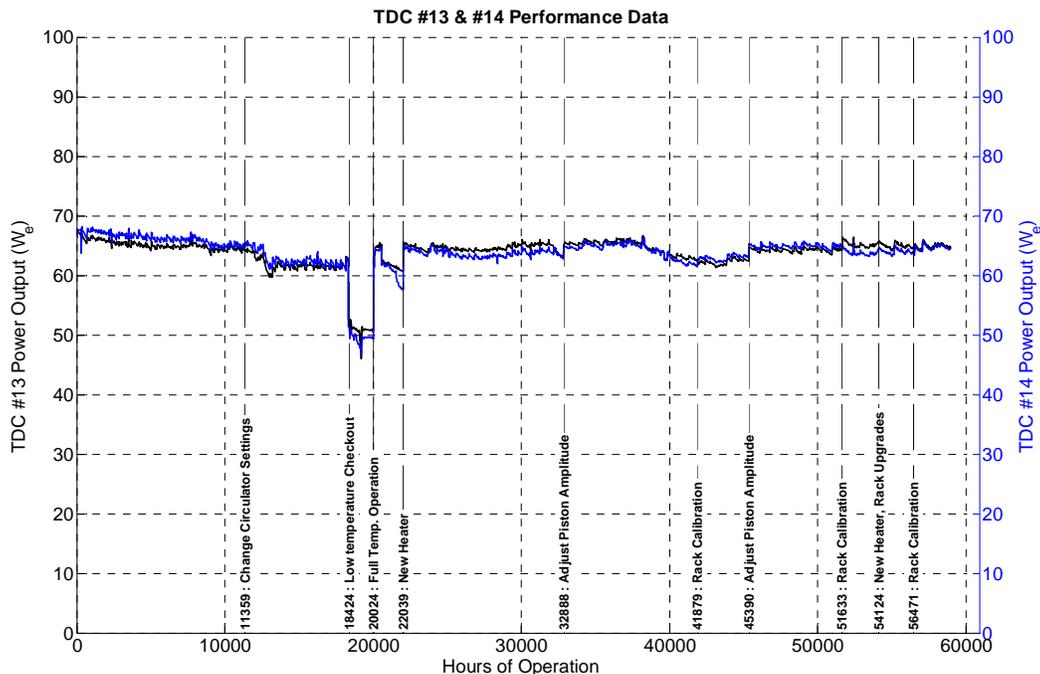


Figure 2.—TDCs #13 and #14 performance data through 60,000 hr of operation.

data that can be attributed to support facility interruptions. The presence of the fill line introduces a working gas leak path, and the convertor still requires periodic charge pressure adjustments approximately every two weeks. These periodic charge pressure adjustments manifest as the “saw-tooth” fluctuations in the plot of power output. The effect of small changes in charge pressure have been quantified, but were not used to correct the data shown in the plot below. Cartridge heaters that provide heat input also introduced performance variability, since their usable life is less than the desired length of extended operation. The cartridges were replaced at 22,000 and 54,000 hr. Other events that introduced disturbances in the data included manual shutdowns for equipment calibration, controller hardware drift, ambient temperature fluctuations, nuisance protection shutdowns, and building power outages. The zener diode-based controller required adjustment at around 25,000 hr to maintain constant convertor piston amplitude. On several occasions, the ambient temperature drifted due to air conditioning malfunctions and caused an observable change in the convertor operation. Similarly, the cold-end temperature control system required maintenance, such as fluid concentration adjustments, or filter cleaning. On many occasions that are not explicitly identified in the plot, automated shutdowns were initiated by the data system monitoring software. Many of these were due to electrical noise interfering with the piston overstroke detection circuitry, while others were due to thermocouple failure. Recently, a backup generator has been connected to power the laboratory to sustain operation in the event of a city power grid outage.

2.2 TDCs #15 and #16

Two more TDCs were put on extended operation in March 2005. These units are identical to TDCs #13 and #14, and are the second longest-running convertors in the Stirling research laboratory with 49,000 hr each. These convertors have been discussed previously in Reference 1 and 3. A plot of convertor performance data through 49,000 hr is shown in Figure 3. Initially, these convertors were operated at a limited hot-end temperature of 500 °C to mitigate regenerator oxidation that was observed in TDCs #13 and #14. The convertor pressure joints were welded at 4,400 hr in the same fashion as

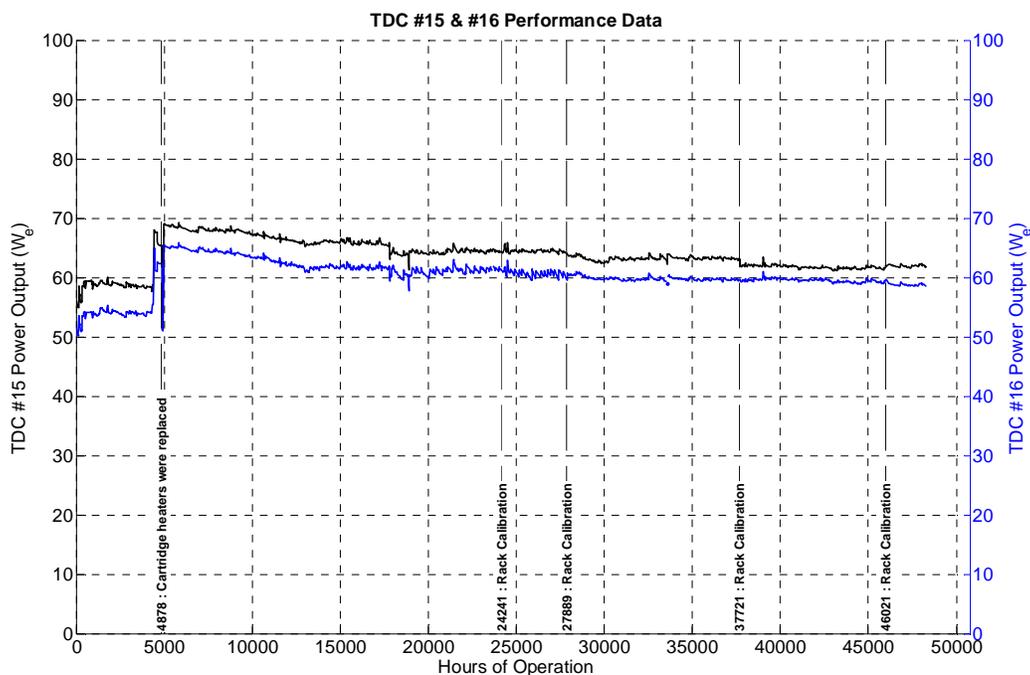


Figure 3.—TDCs #15 and #16 performance data through 49,000 hr of operation.

described for TDCs #13 and #14. These convertors required cartridge heater replacement at 4,900 hr, which was earlier than TDC #13 and #14. This was attributed to improper cleaning after the cartridge lead wire braze operation. The method of lead wire attachment was revised and the replacement cartridges have performed without failure to date, meaning this particular set of cartridge heaters has lasted for over 44,000 hr. The only other activities of note were manual shutdowns to calibrate instrumentation. These are noted on the plot at the appropriate points in time. The slight decrease in performance from 5,000 to 15,000 hr could be attributed to variations in the cold-end temperature control hardware. Currently an open-bath laboratory circulator is employed to flow a water-glycol mixture around the rejection zone of the circulator. This configuration runs in an open-loop mode, so changes in the mixture would affect the flow of the fluid, and thus affect the cold-end temperature. As such, periodic adjustments to the circulator fluid must be made to maintain constant conditions. Similarly, the convertors required periodic adjustments to the charge pressure, which manifests as the “saw-tooth” variation in the plot of power output. The sources of disturbance to steady operation discussed in the section for TDCs #13 and #14 also existed for these convertors, namely ambient temperature fluctuations, nuisance shutdowns due to instrumentation failures, controller hardware drift, and building power outages.

2.3 ASC-0s #3 and #4

The development of the Sunpower ASC began in 2003 with a NASA contract to develop a high-efficiency (up to 40 percent thermal-to-electric) convertor for the next generation radioisotope power system. During Phases I and II of the contract, Sunpower designed and fabricated the convertor model ASC-1, which used MarM-247 heater heads to permit operation at 850 °C. These convertors demonstrated a conversion efficiency of 38 percent. The success of the initial phases led to the redirection of the SRG-110 project, and the replanning of the Sunpower convertor development contract. Sunpower then designed and fabricated the ASC-E convertors, which were tailored for the ASRG EU. Sunpower was also directed to supply additional units for extended operation at GRC. The first of these additional units was convertor model ASC-0. The ASC-1 design made use of MarM-247, but was not a hermetically sealed convertor. At the time the ASC-0 units were requested, the knowledge to hermetically seal a MarM-247 heater head had yet to be developed. To expedite convertor delivery and generation of extended operation data, the decision was made to use Inconel 718 for the ASC-0 design, for which the capability to hermetically seal was already in place. Similarly, the ASC-E design also made use of Inconel 718. The use of Inconel 718 in the ASC-0 design is the reason it was given a preceding model number, even though it chronologically followed the ASC-1 design. The ASC-0 pressure joints were welded, but the helium fill tube was left with an attached isolation valve to permit connection to a working gas sampling and charge pressure management system. Thus, the convertors delivered were not completely hermetically sealed, but had no o-ring joints at the heater head and alternator housing that would normally exist in a non-hermetic convertor.

Four ASC-0 units were delivered to GRC in 2006 and 2007. These convertors have been discussed previously in References 1 and 3. The first pair, (ASC-0s #1 and #2), were operated for a short time in air for checkout testing, and then underwent 15,000 hr of operation in a thermal vacuum environment. The second pair (ASC-0s #3 and #4), began operation in August 2007 and have been operating in air since delivery. The convertors produce approximately 75 W_e at operating temperatures of 650 °C hot end and 90 °C cold end. A summary of performance data for ASC-0s #3 and #4 through 25,000 hr is shown in Figure 4. Initial convertor operation was at full temperature and power. At approximately 3,990 hr, a manual shutdown and restart was executed for scheduled test rack maintenance, consisting mostly of instrument calibration. Following this maintenance activity, the convertor performance became noticeably more variable. This is thought to be due to a poor electrical connection in the test rack that arose during the maintenance activity. At 7,400 hr, the convertors underwent launch simulation vibration testing, which exposed each to 8.7 g_{rms} in all three axes. The convertors also underwent heater head diameter measurements that will provide data for Inconel 718 creep model validation. This measurement was performed using a laser micrometer providing a resolution of 0.05 μm. The micrometer was swept along

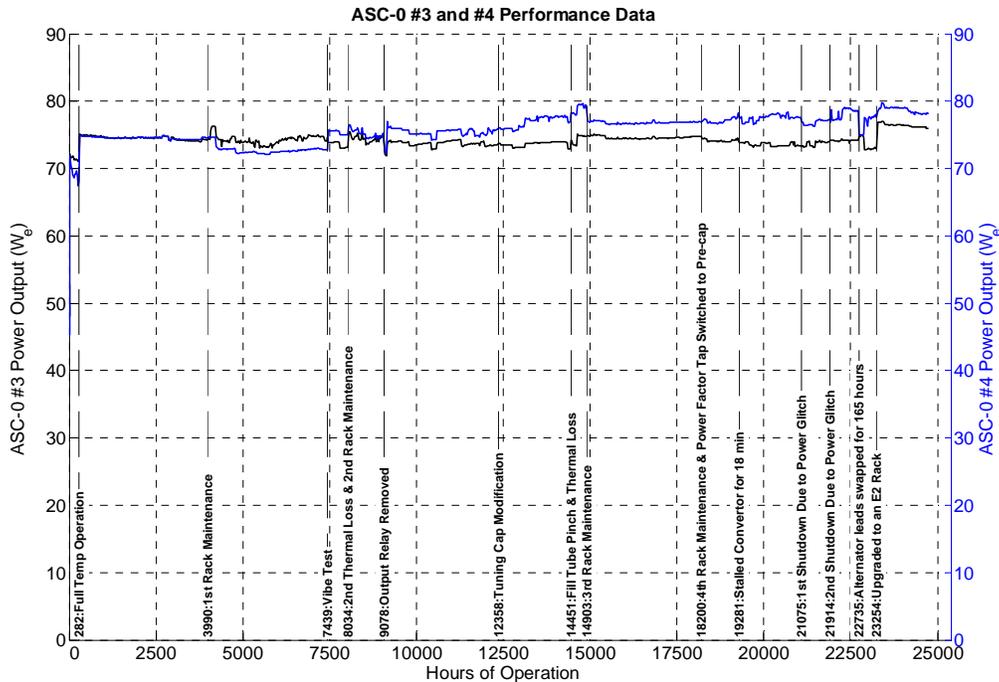


Figure 4.—ASC-0s #3 and #4 performance data through 25,000 hr of operation.

the axis of the heater head, and recorded diameter as a function of axial position at eight circumferential locations. The heater head will be measured in the same fashion again in the future, which will reveal creep if any has occurred. The converters resumed operation following launch simulation vibration testing, emulating the sequence that the flight converters will undergo. From this point and through 14,400 hr, various activities took place to pinpoint the source of faulty power pathway connection in the test rack, but no root cause was identified. During this period, the variable nature of the converter power output continued.

After 14,400 hr, the converter helium fill tubes were pinched, completely hermetically sealing the working gas. The converters were leak tested before and after the fill tube pinch. Both leak rates were below the requirement for flight units, indicating successful hermetic sealing. Similarly, converter performance was compared before and after the fill tube pinch. No negative effect on converter operation was observed. In fact, the converters appeared to perform slightly better with the pinched tube. Shortly thereafter, at 14,900 hr, another scheduled rack maintenance activity was performed. Interestingly, the converter performance was noticeably steadier following this activity. This suggests that either the startup and shutdown transient or the activity in the test rack was to blame. At 18,200 hr, operation was shut down for yet another test rack maintenance activity, after which the more-variable converter performance returned. At 23,250 hr, the entire test rack was upgraded to a more recent design that incorporated changes to achieve a more robust power pathway. Following this test rack upgrade, the converter performance has been as steady as that initially observed before the first test rack maintenance, suggesting once again that the aforementioned variable performance was due to the test rack. As was true for other test stations, steady operation was disturbed on multiple occasions due to facility issues such as power outages, ambient temperature changes, circulator fluid adjustments, and nuisance shutdowns due to instrumentation.

2.4 ASRG EU (ASC-Es #2 and #3)

The ASRG EU was designed and fabricated by LMSS under contract to DOE. The generator design integrates two Sunpower ASC-Es in the dual-opposed configuration, and uses electric heat sources in place of GPHS modules (Ref. 4). Aside from the electric heat sources, the EU design emulates a flight unit. The ASC-E was designed specifically for the ASRG EU. It uses Inconel 718 for the heater head, and is a completely hermetically sealed convertor (pressure joints are welded and helium fill tube is pinched). LMSS delivered the ASRG EU to GRC in August 2008 after completing their own set of checkout tests. The ASRG EU has since accumulated 19,000 hr of operation at GRC. The ASRG EU was most recently discussed in Reference 4. The convertors produce approximately 65 W_e at operating temperatures of 625 °C hot end and 63 °C cold end. When assembled into a generator, the convertors are cooled by connection of the rejection end to the housing. The EU is being operated in the vertical orientation and cooled with chilled air, which limits the ability to control the convertor's cold-end temperature relative to other test stations in the laboratory. A summary of convertor performance for the ASRG-EU convertors through 19,000 hr is shown in Figure 5. The ASRG EU was operated on and alternating current (AC) bus control (rather than a flight-like controller) for the first 5,500 hr. During this time, fluctuations in convertor performance were observed and attributed to variation in the test rack power path impedance. Test rack improvements were made on two occasions during this time, at 2,100 and 4,800 hr. LMSS then delivered the ASC Controller Unit (ACU), which was designed to control operation of the convertors in a fashion similar to that used in flight. The control algorithm for flight employs active-power-factor-correction, and needs no tuning capacitance (Ref. 7). As such, the controller must actively synchronize the piston motions to achieve dynamic balance. The ASRG EU began operating with the ACU at the 5,200-hr mark. The ASRG EU has continued operation on the ACU since then, except for one brief period of operation on AC bus control for specific tests. Between 5,200 and 13,500 hr, many other tests were conducted. However, from the 13,500-hr mark to present, operation has been maintained as best as possible at the nominal conditions. This region is most useful for observing steady long-term data. As can be seen, the performance is steady, and matches well to the initial ACU operation from the 6,000 to 8,000-hr marks. This suggests the system (ASRG plus ACU) responds in a repeatable fashion when returning to the same operating conditions.

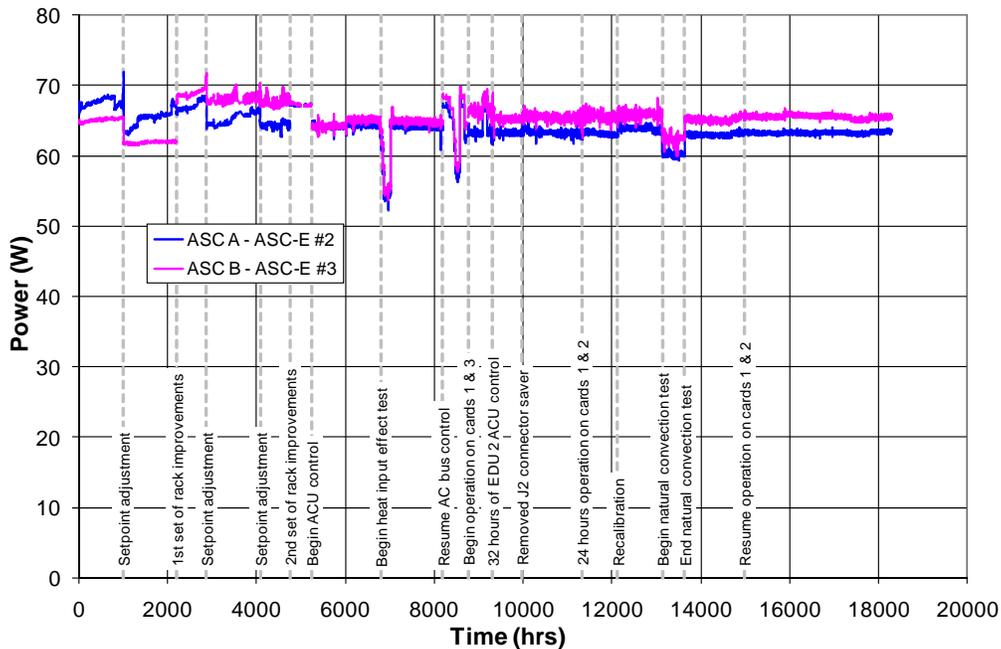


Figure 5.—ASRG-EU (ASC-Es #2 and #3) performance data through 19,000 hr of operation.

2.5 ASC-E #1 and #4

Sunpower fabricated four ASC-E units in support of the ASRG EU. Two of these were integrated into the ASRG EU (ASC-E #2 and #3). The other two converters (ASC-E #1 and #4) were delivered to GRC to undergo extended operation. These converters were assembled into support hardware that visually resembles the ASRG EU housing, but uses liquid coolant flow to control the convertor cold-end temperature, rather than chilled air convection cooling used for the ASRG EU (Ref. 3). These converters also underwent heater head diameter measurements for evaluation of long-term creep of Inconel 718 on an operating convertor. These converters began extended operation in December 2009 and have accumulated 10,000 hr as of July 1, 2011. A plot of convertor performance is shown in Figure 6. The converters produce approximately 65 W_e at operating temperatures of 650 °C hot end and 70 °C cold end. At around 1,000 hr of operation, the voltage tap for the power meter that measures convertor power output was moved to the convertor side of the tuning capacitance. This changed the power measurement only because of the resistive losses that exist between these two points. The tuning capacitance ideally does not dissipate any power, except for that associated with its series-equivalent resistance. There was an unexpected 7- W_e drop in power output from ASC-E #1 near 4,500 hr of operation. At this time, the power path was inspected for loose connections. No faulty connections were identified in the power path and operation resumed, but ASC-E #1 never returned to its original power output level. Between 7,000 and 8,000 hr, the converters were operated with the alternator leads swapped at their connection to the test rack. This was done to determine if the power loss was due to a faulty connection in the test rack, or an issue on the convertor side of the alternator connection. The ASC-E #1 power output did not return to its initial-operation level, suggesting the test rack was not the cause of the 7- W_e drop. This event is under investigation by a team at GRC to determine the root cause. Other instances of non-flatline power output have been attributed to shutdowns and fluctuations in ambient temperature.

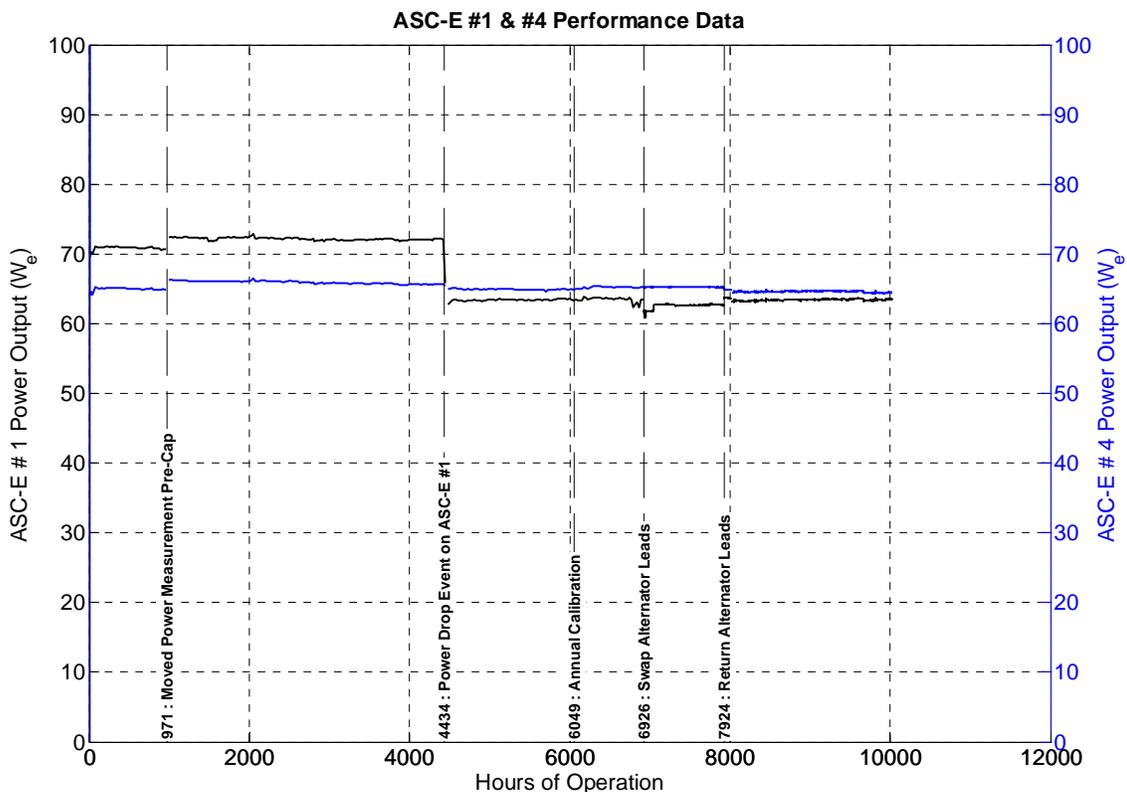


Figure 6.—ASC-Es #1 and #4 performance data through 10,000 hr.

2.6 ASC-E2s #1 and #2

Another task under the Phase III redirection of the Sunpower ASC development contract was the design and fabrication of several hermetically-sealed MarM-247 heater head convertors. MarM-247 was successfully demonstrated on a convertor during Phase II of the contract, on the ASC-1 units, but these were not hermetically sealed. Following completion of the ASC-E units, Sunpower proceeded to design and fabricate eight ASC-E2 units. The ASC-E2 design is the same as the ASC-E, but uses MarM-247 for the heater head, thus ASC-E2 is the first convertor model to have the high-temperature heater head material and be completely hermetically sealed. MarM-247 permits hot-end operating temperatures up to 850 °C, which increases the conversion efficiency. The ASC-E2 was designed to be as flight-like as possible, and is physically representative of the units that will be integrated into the flight generator. The ASC-E2s have completed or are undergoing a GRC test sequence consisting of the following: workmanship vibration testing, performance mapping, and extended operation (Ref. 2). Workmanship vibration testing was performed following convertor final hermetic sealing and just prior to delivery to GRC. Performance mapping consisted of operating the convertor at different cold-end temperatures and heat inputs to simulate conditions expected during a mission. An operating condition representing the beginning-of-mission (BOM) low-rejection (LR) temperature was chosen for extended operation. This represents operation of the generator with maximum heat input from the GPHS module and exposure to a deep-space sink temperature. Other operating conditions simulated included end-of-mission (EOM) LR and BOM or EOM high rejection (HR).

ASC-E2 #1 and #2 were the first convertors of this design to be fabricated. The convertors were not delivered as a pair, due to the discovery of a heater head manufacturing flaw in ASC-E2 #1 resulting in leakage of the helium working gas over time. ASC-E2 #2 was delivered first to GRC as a single unit in February 2010 (Ref. 2). ASC-E2 #2 completed the GRC test sequence, and has accumulated 2,700 hr of operation thus far. A plot of 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 BOM LR. The initial 280 hr of operation included checkout tests and performance mapping, after which extended operation was initiated at BOM LR. A series of nuisance shutdowns occurred around 400 hr and these data do not reflect unsteady convertor performance. Normally, the heat input to the convertor is controlled via a constant temperature control loop. With this, the hot-end temperature stays constant but the thermal power input could dither as the control loop maintains its set point. At other times, constant heat input was explored to more accurately simulate heat input from a radioisotope source. Such was the case between 400 and 742 hr. Between 406 and 568 hr, the downward trend in power output was due to the use of constant heat input mode. Malfunctions in the thermal power input feedback signal used by the constant heat input controller resulted in unsteady heat input. These issues were resolved at the 568-hr mark and performance became noticeably steadier. Between 742 and 1,265 hr, other tests were performed at the request of LMSS, which deviated from the BOM LR operating condition. A similar test took place between 2,084 and 2,327 hr. Outside of these regions, the operating conditions were held steady at the BOM LR conditions. During the times that conditions were steady, the convertor performance was steady. Other minor disturbances in the plot were caused by ambient temperature fluctuations. ASC-E2 #2 was shut down after 2,446 hr of operation, after which it was paired with ASC-E2 #1 and underwent an electromagnetic interference (EMI) characterization test. Currently, ASC-E2 #2 is idle and will continue operation in the dual-opposed configuration with ASC-E2 #1 once testing is completed.

ASC-E2 #1 was delivered to GRC in April 2010. Delivery of ASC-E2 #1 was delayed due to the discovery of a heater head manufacturing flaw that results in helium leakage. A plot of convertor performance is shown in Figure 7. ASC-E2 #1 completed performance mapping and initial extended operation within the first 888 hr of operation. Tests similar to those performed on ASC-E2 #2 were also performed, such as an operating frequency sweep that took place between the hours of 605 and 888. ASC-E2 #1 then underwent EMI characterization in the dual-opposed configuration with ASC-E2 #2, which took place between 888 and 1,143 hr of operation. ASC-E2 #1 was then manually shut down and fitted with a “compact” heat source. The compact heat source was designed to reduce thermal losses through

the insulation relative to the standard heat source used for ASC-E2 operation. For comparison, with the baseline ASC-E2 heat source, the losses are approximately $170 \text{ W}_{\text{th}}$ at $850 \text{ }^\circ\text{C}$ hot-end temperature, while with the compact heat source the losses were reduced to 75 W_{th} . Performance mapping with this heat source took place between 1,143 and 1,476 hr, after which extended operation at BOM LR was initiated. Steady conditions were maintained between 1,476 and 3,849 hr. During this time, the effect of the known working gas leakage manifested. Notice the downward trend in power output that was corrected on two occasions (at 2,629 and 3,223 hr). The corrections were made by increasing the piston amplitude to return to the baseline BOM LR power output. Data from this region are being used to validate the prediction of power loss versus time due to the helium leakage. Between 3,849 and 4,696 hr, another off-nominal operating condition test was performed. The compact heat source required replacement at 4,696 hr, at which time a standard ASC-E2 heat source was installed. From 4,696 to 6,097 hr, operation continued at the baseline BOM LR condition. The downward trend in power output was observed again, but was more variable due to nuisance shutdowns and temporary disturbances in the ambient temperature. Between 6,097 and 6,193 hr, a test was performed to experimentally measure the convertor natural frequency while operating. This test will be performed periodically in the future to further track the effect of the helium leakage. To date, ASC-E2 #1 has operated for over 6,200 hr, making it the leader in $850 \text{ }^\circ\text{C}$ convertor operation. ASC-E2 #1 will be paired with ASC-E2 #2 in the future for continued extended operation.

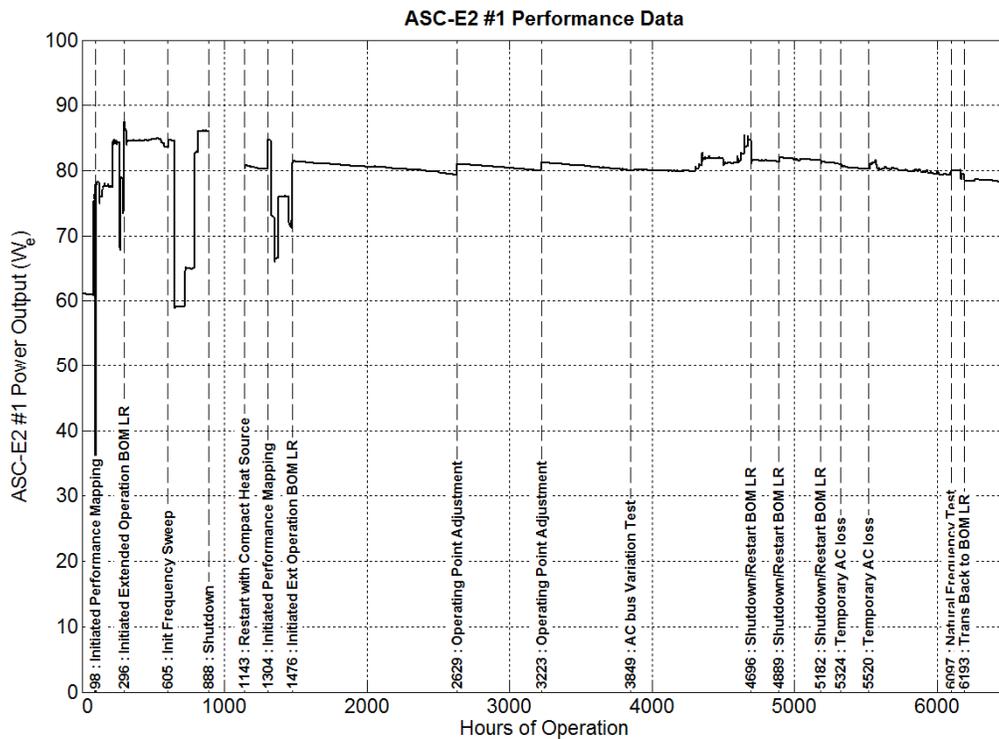


Figure 7.—ASC-E2 #1 performance data through 6,500 hr.

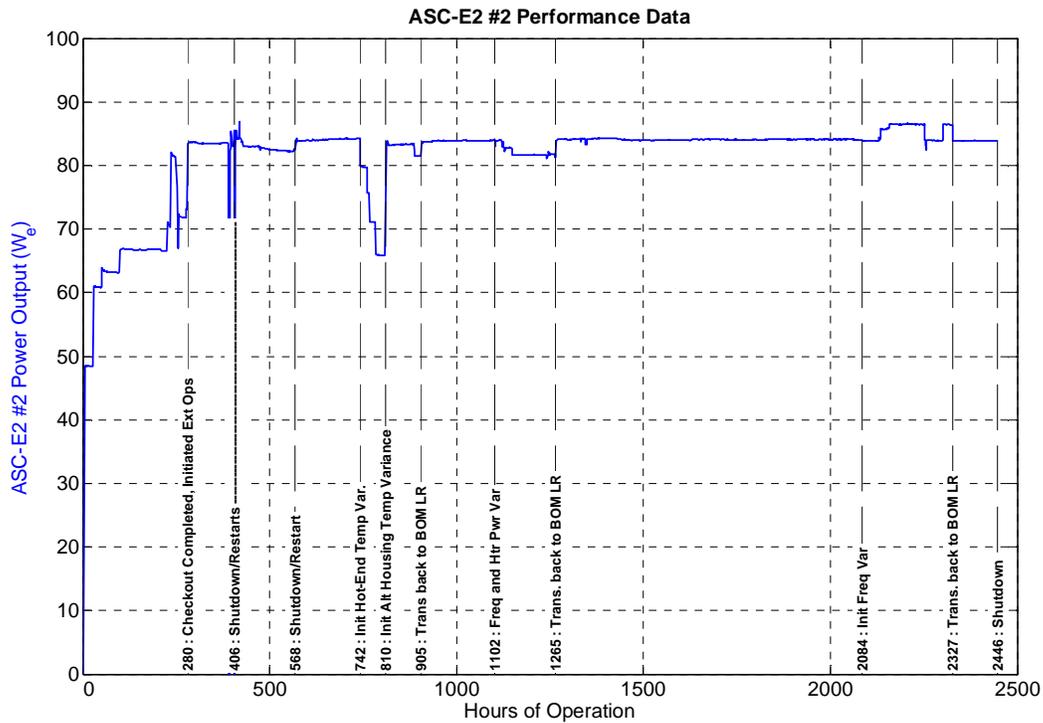


Figure 8.—ASC-E2 #2 performance data through 2,500 hr.

2.7 ASC-E2s #3 and #4

The second pair of ASC-E2 units, #3 and #4, were delivered to GRC in April 2010. These convertors were delivered as a pair, and were operated exclusively in the dual-opposed vertical configuration, similar to the arrangement of the convertors in the ASRG EU (Ref. 2). A plot of convertor performance is shown in Figure 9. Checkout testing and performance mapping took place during the initial 213 hr of operation. From 213 to 618 hr, user adjustments were made to maintain the BOM LR condition. Both constant heat input and constant temperature modes were used for heat input control. Adjustments were necessary to hone in on the desired operating condition in response to transients. These transients have been observed to take on the order of one week to achieve steady operation. This can be attributed to the slow thermal response time of the hot-end insulation assembly. Between 618 and 802 hr, a frequency sweep was performed similar to that described for ASC-E2s #1 and #2. Outside of user adjustments and special tests, the convertor performance was steady with other minor disturbances due to ambient temperature fluctuations. Following the operation described here, the convertors were transported to Lockheed Martin Coherent Technologies (LMCT) for controller development. These convertors will be returned to GRC for continued extended operation in 2012.

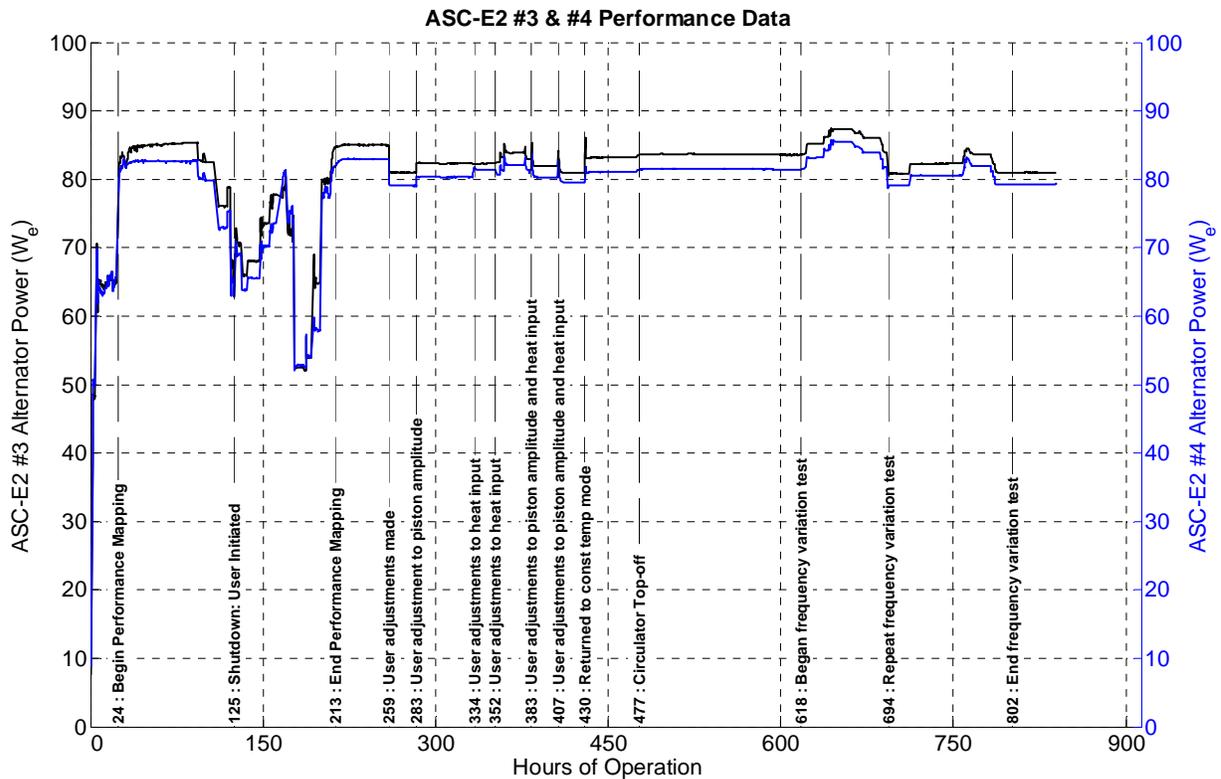


Figure 9.—ASC-E2s #3 and #4 performance data through 800 hr of operation.

2.8 ASC-E2s #5 and #6

The third pair of ASC-E2 units, #5 and #6, was delivered to GRC in July 2010. These were also delivered as a pair, and operated exclusively in the dual-opposed vertical configuration (Ref. 2). A plot of convertor performance is shown in Figure 10. The convertors completed workmanship vibration testing, performance mapping, and are undergoing extended operation at the baseline BOM LR condition. The performance data between 1,194 and 1,914 hr show an increase in power output. This has been attributed to fluid concentration changes in the cold-end circulator. For performance mapping, a specific mixture of glycol and water was required to achieve the desired temperatures. It has been observed that during extended operation, the water may slowly evaporate, altering the viscosity of the fluid. Adjustments to the circulator fluid temperature and concentration were made after the 1914-hr mark to maintain the BOM LR condition. As can be seen, once the fluid was stabilized, the convertor performance also stabilized. Between 2,202 and 2,323 hr, another off-nominal test was performed during which the alternator housing temperature was varied. Between 2,323 and 2,480 hr, the convertors were operated at EOM LR, which resulted in a lower power output as would be expected. During this time, the ASC-E2 #5 heat source began failing, which resulted in the fluctuation in power output near the end of that time period. At 2,665 hr, each convertor heat source was replaced and operation resumed at EOM LR. Between 2,883 and 4,233 hr, operation at the high rejection temperature was explored to ascertain its effect on convertor performance. During this time, the convertor performance was visibly less steady, but this can also be attributed to the aforementioned variability in the rejection temperature control. At the high rejection temperature, the fluid of the open-bath circulator requires more frequent adjustments to maintain steady operating conditions. Many adjustments were made at and around the 3,019-hr mark. Furthermore, a particularly large disturbance in the ambient temperature resulted in the performance disturbance seen at the 3,823-hr mark. After 4,233 hr, the operating condition was returned to BOM LR. Convertor performance has been steady since this time, and the convertors are still operating. As of July 1, the convertors have each accumulated 4,800 hr of operation.

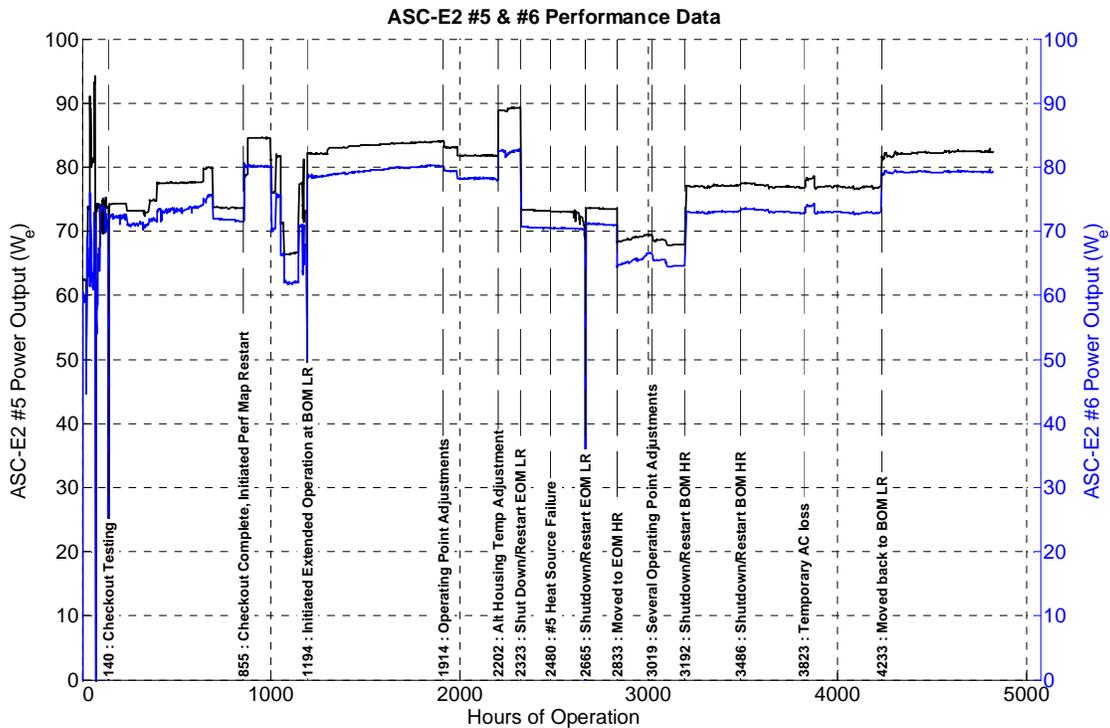


Figure 10.—ASC-E2s #5 and #6 performance data through 4,800 hr of operation.

2.9 ASC-E2s #7 and #8

Two ASC-E2 units (#7 and #8) were selected to undergo additional “durability” tests (Ref. 2). These tests are intended to experimentally demonstrate the margins that exist in the ASC-E2 design. The converters will be subjected to conditions beyond that expected during normal operation. The tests include start/stop cycling, overstroke due to launch vibration, and centrifugal acceleration. The tests are not intended to cause damage that will shorten converter life. The alternator housing will be removed and the converter components will be inspected after each durability test. For this purpose, the converters were not hermetically sealed, but instead have a removable alternator housing. Following these tests, the converters will undergo the standard hermetic sealing, and then continue extended operation.

3.0 Maintaining Steady Operating Conditions

The data presented thus far show that converter performance has been steady when the operating conditions were precisely maintained. When user adjustments were made, the response in converter performance was evident. When disturbances were introduced involuntarily, the response was also evident. If ignoring periods where these events occurred, the performance data were flatline. User adjustments were necessary on several occasions to perform investigative tests, or to supply data to LMSS. However, there were several periods during which the user made no adjustments, but the operating conditions were disrupted by spontaneous changes in support systems and the ambient environment. These disruptions have been attributed to variability of temperature control methods, nuisance shutdowns, ambient environment fluctuations, and long-term thermal transients. In the case of temperature control methods, changes in the heat input hardware such as thermal connectivity between the heat source and converter, or long-term aging of the hot-end insulation have caused long-term thermal transients that require periodic adjustment. Similarly, changes in the fluid circulation system that is employed to control converter cold-end temperature also caused deviations in the operating point. Since the circulator is an open bath, the glycol-water mixture viscosity may change over time as water

evaporates. It is currently a regularly-scheduled maintenance task to add distilled water to the fluid to maintain level and concentration. It was also discovered that ambient temperature fluctuations manifest in convertor performance data. While the room air has a dedicated temperature control system, it is still affected by the season, and the environment surrounding the test article may vary by 3 °C because of this. Similarly, when the room air conditioning system malfunctions, an even larger rise in the ambient environment results. Care has been taken when analyzing convertor performance data to attribute performance changes to such an event when necessary. While the desire is to maintain non-stop operation, nuisance shutdowns have been found to be unavoidable over long periods of time. The majority of nuisance shutdowns have been attributed to instrumentation failure, such as a broken thermocouple lead, which the data system interprets as an over-temperature alarm, or interference in the overstroke protection circuit signal. Other nuisance shutdowns have been experienced due to electric grid supply failures. Despite the presence of an uninterruptible power supply (UPS), even short-term noise on the city power grid has been found to trip controlled shutdowns, as in some cases the UPS interprets this as a loss of grid power. Recently, a power conditioner, automated transfer switch, and backup natural gas generator have become operational, which makes the test stations immune to both complete grid outages and temporary “dirty” grid power.

4.0 Conclusion

For the purpose of generating life and reliability data in support of Stirling energy conversion for spaceflight, NASA GRC has been operating several Stirling convertors in extended mode. Convertor performance data are recorded continuously, and analyzed periodically to ascertain long-term trends. To date, GRC has operated 38 convertors with a cumulative runtime exceeding 400,000 hr. Currently, 18 convertors are either operating continuously, or are slated to continue continuous operation. These 18 convertors have accumulated over 350,000 hr. Included are four Infinia TDCs, and 14 Sunpower ASCs from various stages of technology development. The data support the viability of Stirling conversion in space, as long life can be achieved by using non-contacting oscillating component technology. The performance data show that long-term convertor operation is steady when operating conditions are maintained, and disruptions from the support facility are discarded. Disruptions of steady operating conditions have been attributed to variability in temperature control methods, nuisance shutdowns, ambient environment fluctuations, and long-term thermal transients.

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14. ABSTRACT NASA Glenn Research Center (GRC) has been supporting development of free-piston Stirling conversion technology for spaceflight electrical power generation since 1999. GRC has also been supporting the development of the Advanced Stirling Radioisotope Generator (ASRG) since 2006. A key element of the ASRG project is providing life, reliability, and performance data for the Advanced Stirling Convertor (ASC). The Thermal Energy Conversion branch at GRC is conducting extended operation of several free-piston Stirling convertors. The goal of this effort is to generate long-term performance data (tens of thousands of hours) on multiple units to build a life and reliability database. Currently, GRC is operating 18 convertors. This hardware set includes Technology Demonstration Convertors (TDCs) from Infinia Corporation, of which one pair (TDCs #13 and #14) has accumulated over 60,000 hr (6.8 years) of operation. Also under test are various Sunpower, Inc. convertors that were fabricated during the ASC development activity, including ASC-0, ASC-E (including those in the ASRG engineering unit), and ASC-E2. The ASC-E2s also completed, or are in progress of completing workmanship vibration testing, performance mapping, and extended operation. Two ASC-E2 units will also be used for durability testing, during which components will be stressed to levels above nominal mission usage. Extended operation data analyses from these tests are covered in this paper.					
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