



Advanced Stirling Convertor (ASC-E2) Performance Testing at NASA Glenn Research Center

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Abstract

The National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) has been supporting development of the Advanced Stirling Radioisotope Generator (ASRG) since 2006. A key element of the ASRG Project is providing life, reliability, and performance testing of the Advanced Stirling Convertor (ASC). For this purpose, four pairs of ASCs capable of operating to 850 °C and designated with the model number ASC-E2, were delivered by Sunpower of Athens, Ohio, to GRC in 2010. The ASC-E2s underwent a series of tests that included workmanship vibration testing, performance mapping, and extended operation. Workmanship vibration testing was performed following fabrication of each convertor to verify proper hardware build. Performance mapping consisted of operating each convertor at various conditions representing the range expected during a mission. Included were conditions representing beginning-of-mission (BOM), end-of-mission (EOM), and fueling. This same series of tests was performed by Sunpower prior to ASC-E2 delivery. The data generated during the GRC test were compared to performance before delivery. Extended operation consisted of a 500-hr period of operation with conditions maintained at the BOM point. This was performed to demonstrate steady convertor performance following performance mapping. Following this initial 500-hr period, the ASC-E2s will continue extended operation, controller development and special durability testing, during which the goal is to accumulate tens of thousands of hours of operation. Data collected during extended operation will support reliability analysis. Performance data from these tests is summarized in this paper.

Nomenclature

AC	Alternating Current
ASC	Advanced Stirling Convertor
ASRG	Advanced Stirling Radioisotope Generator
BOM	Beginning of Mission
CSAF	Cold-Side Adapter Flange
DC	Direct current
EMI	Electromagnetic Interference
EOM	End of Mission
GPHS	General Purpose Heat Source
GRC	Glenn Research Center
NASA	National Aeronautics and Space Administration
PID	Proportional Integral Derivative
RTG	Radioisotope Thermoelectric Generators
TDC	Technology Demonstration Convertor
UPS	Uninterruptible Power Supply

Introduction

The Thermal Energy Conversion Branch at the National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) has been supporting the development of the Advanced Stirling Radioisotope Generator (ASRG) (Refs. 1 and 2). Use of Stirling technology quadruples the efficiency of thermal-to-electrical power conversion when compared to Radioisotope Thermoelectric Generators (RTGs), which significantly reduces the amount of radioisotope fuel required for a given power level (Ref. 3). Demonstrating reliability of the ASC is one of the components vital to ensuring reliability of the ASRG.

GRC is providing life and reliability data to the ASRG project in a multitude of areas, including structural dynamics, electromagnetic compatibility (EMC), high-temperature materials, and organics (Ref. 4). GRC is also conducting extended operation life testing at the convertor level. To date, a total of 38 Stirling convertors have been operated at GRC in support of a space radioisotope power system development, with a total cumulative runtime exceeding 358,000 hr (Ref. 1). Two units in particular, Technology Demonstration Convertors (TDCs) #13 and #14 have each operated for over 54,700 hr. Amongst these 38 convertors are four pairs of ASC-E2s (e.g., Figure 1). The ASC-E2 model is the latest design from Sunpower, Inc. of Athens, Ohio, and is physically representative of the units that will be integrated into the flight unit generator. The ASC-E2 uses MarM-247 for the heater head material and is capable of continuous operation at 850 °C with a life no less than 17 years. During flight, the operating temperature ratio is expected to range from 3.1 to 3.6.

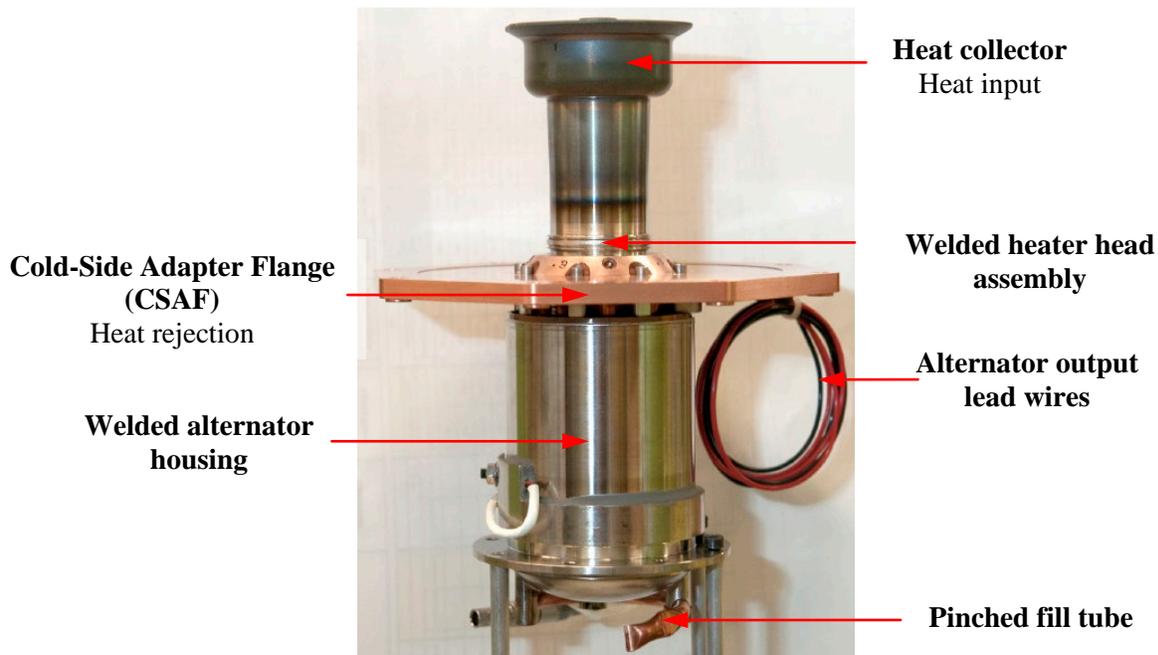


Figure 1.—Example ASC-E2 upon delivery to GRC.

ASC-E2s #1 through #8 arrived at GRC between February and August 2010. The first three pairs (#1 through #6) were hermetically sealed by welding pressure vessel joints and pinching the helium fill tubes. These convertors have completed or are undergoing a standard test sequence including workmanship vibration testing, insulation loss characterization, performance mapping, and extended operation. Workmanship vibration testing was performed following convertor final hermetic sealing and prior to delivery to GRC. The purpose of this test was to demonstrate proper fabrication by subjecting each convertor to 6.8 g_{rms} vibration with a frequency range of 20 to 2000 kHz, per NASA-STD-7001. Following the workmanship vibration tests, the convertors underwent final performance testing at Sunpower. During this test, the convertor performance was measured over a range of operating conditions representing various mission scenarios, as identified in the ASC-E2 product specification.

Following delivery to GRC and installation onto the test stands, the convertors underwent thermal insulation loss characterization, which generated data to enable calculation of net conversion efficiency. Following this, the performance mapping test was executed, which was a duplication of the final performance test performed by Sunpower. This test provided data to compare convertor performance before and after delivery to ensure the hardware remained unaltered during transit. The data also served the purpose of establishing a baseline for convertor performance at GRC, as well as comparison to the ASC-E2 product specification. The convertors then underwent at least 500 hr of continuous operation during which the operating condition was maintained at the beginning-of-mission (BOM) low-rejection temperature point. This test provided performance data for demonstrating stable convertor operation by comparing the initial and final performance over this time span.

The latter two ASC-E2s, #7 and #8, were fabricated with removable, non-hermetic pressure vessels, as these convertors will undergo durability testing, permitting disassembly and inspection of internal components following each test. As such, the test sequence is different than the first three convertor pairs. These convertors did not undergo workmanship vibration testing, but will still undergo insulation loss characterization and performance mapping prior to execution of the durability tests. Following completion of the durability tests, the convertors will be returned to Sunpower to complete hermetic processing, after which workmanship vibration and final performance testing will be performed.

GRC ASC-E2 Test Setup Overview

A diagram showing component interconnections of the current GRC test station design for ASC-E2 operation is shown in Figure 2. The convertor is heated by an electric heat source, which is driven by a programmable power supply. This power supply is controlled by a proportional-integral-derivative (PID) loop, which can use either hot-end temperature or heater power for feedback. The cold-end temperature is controlled by a laboratory circulator, which flows fluid through coolant collars attached to the cold-side adapter flange (CSAF). A second circulator may be used to flow fluid through a heat exchanger around the alternator housing. Inside the test rack, a tuning capacitance is connected in series with the alternator output. A Pearson coil is used to measure alternator current. If operating a pair of convertors, the other convertor would be connected electrically in parallel between the capacitance and load. The alternator connector voltage and current signal from the Pearson coil are connected to a power meter. The load consists of three 1- Ω resistors connected in parallel, producing 1/3 Ω . An alternating current (AC) power supply was connected to this load through a step-down transformer. The AC power supply controls the voltage and frequency across the load, simulating an AC bus for convertor control. This enables independent control of piston amplitude and operating frequency. A failsafe protection circuit can apply an emergency load if an overstroke condition is sensed. Power is provided to the test rack and circulators by an uninterruptible power supply (UPS).

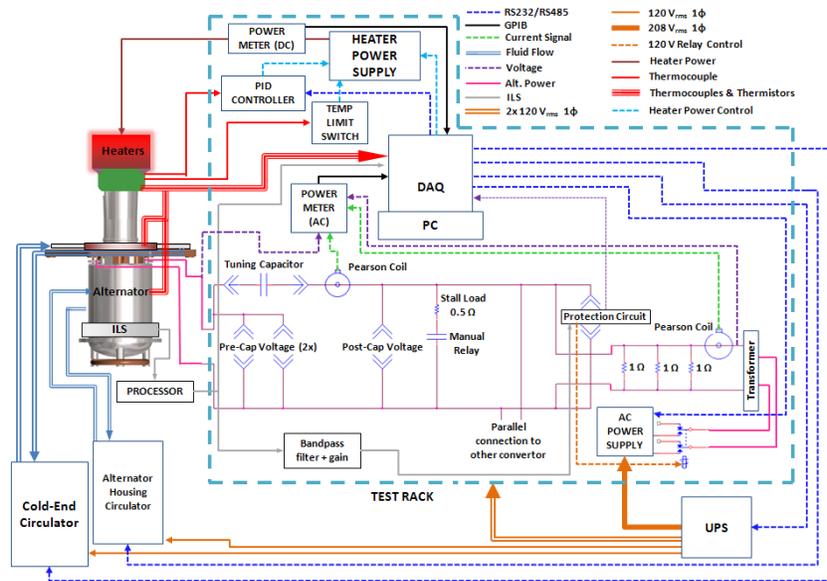


Figure 2.—GRC ASC-E2 test setup overview.

The test setup containing ASC-E2 #1 is shown in Figure 3. ASC-E2 #1 and #2 were not delivered as a pair, so the ability to operate a single convertor with a ballast mass was implemented. The heat input hardware consisted of a spring-loaded electric heat source. Watlow HT Firerod cartridge heaters were chosen for their high maximum use temperature rating of 982 °C. A ceramic stud made of Cotronics Rescor 902 was used to transfer the force of the springs and load the heat source onto the heat collector. A 0.015-inch-thick alumina disk was placed between the heat source and convertor heat collector to prevent diffusion bonding of the two nickel-based components. Volumes inside the insulation box not occupied by microporous insulation were filled with silica blanket insulation (Thermal Ceramics Kaowool). Brazed assemblies that form coolant passages with inlet and outlet tubes were attached to the CSAF for cold-end temperature control. Kapton surface heaters were attached to the alternator housing and a coil of tubing was wound around the alternator housing to effect a heat exchanger. Microporous insulation (Zircar Microsil) was installed around the heat source and heater head. Note that the section view does not show the tubing connecting to the CSAF coolant collars, nor the tubing around the alternator housing. Also not shown in the section view are the alternator housing surface heaters.

The test rack was designed and built to accommodate two convertors, but is also capable of operating a single unit. The path taken by the alternator current to the load was designed to minimize connections. Where possible, an uninterrupted length of wire was used along the power path. Where connections were necessary, solder joints were preferred.

Each convertor was instrumented for temperature measurements with four hot-end thermocouples, two CSAF thermocouples, one CSAF thermistor, and one alternator housing thermocouple. The heat source and coolant temperatures were also measured using thermocouples.

The product specification specifies input temperature using the term “acceptor temperature.” This is the component in the heater head that transfers heat to the working gas. Since the hot-end thermocouples could not be located to directly measure this temperature, a correction was made. The acceptor temperature was defined as the average of the four hot-end thermocouple readings plus 7.5 °C. This offset was determined by Sunpower using a thermal finite element model. Similarly, a correction was made for the rejector; the component that extracts heat from the working gas. In this case, the rejector temperature was defined as the average of the two CSAF thermocouple readings plus 3.5 °C.

The power supplied to the heaters was measured using a Yokogawa WT230 power meter. Alternator output (voltage, current, power, power factor, and frequency) was also measured by a Yokogawa WT230 power meter. The alternator currents were measured using an external sensor, namely a model 411 Pearson coil. The piston amplitude was measured using the convertor’s internal limit sensor (ILS).

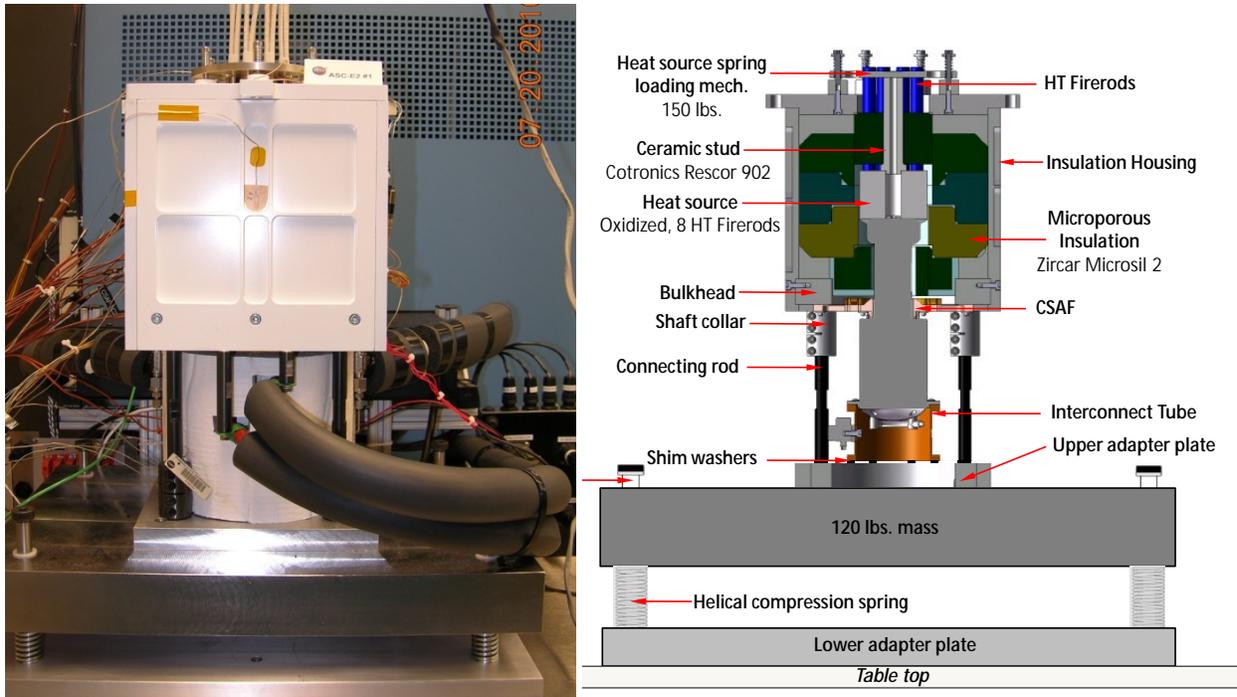


Figure 3.—Completed ASC-E2 single-convertor test article (left), and section view (right).

ASC-E2 #2

The first hermetically sealed MarM-247 convertors delivered by Sunpower were designated with the serial numbers 1 and 2. The goal was to deliver these convertors as a pair to GRC, but because of a manufacturing delay, #1 was delivered after to #2. #2 completed workmanship vibration testing near the end of January 2010, and was delivered to GRC on February 5, 2010. All installation and checkout tasks were completed on #2 by the end of February. #2 was setup in the single vertical configuration with its heater head in the upwards direction.

Thermal insulation loss characterization began on March 5. The method for characterizing insulation losses has been revised since the first ASC-E2 test and will be described in subsequent sections. For #2, a stall load was connected to prevent convertor operation while the hot and cold ends of the convertor were maintained at various temperatures. The hot-end temperature was varied from 550 to 850 °C, while the cold-end temperature was varied from 35 to 90 °C. The heater power required to maintain steady state at each condition was measured. From each heater power, the calculated conduction and radiation heat transfer down the convertor heater head was subtracted. This difference represents the thermal losses through the insulation at each condition. With these data, a correlation was developed relating heat source and hot-end temperature to insulation losses. Net heat input was then defined as heater power minus insulation losses. A non-operating convertor, such as that when the stall load is engaged, does not draw as much thermal power from the heat source as an operating convertor. Because of this, the heat source to hot-end temperature difference realized during thermal loss characterization is smaller than that realized during actual convertor operation. To maintain a given hot-end temperature, the heat source will rise to a higher temperature on an operating convertor than a non-operating convertor. Since the thermal loss characterization was performed on a non-operating convertor, this effect had to be accounted for in order to appropriately calculate insulation losses when operating, even at the same hot-end temperature. To do this, a thermal finite element model of ASC-E2 #2, its heat source, and its insulation was developed to determine the relative dependence of insulation loss on both the hot-end and heat source temperatures.

The method for both executing the thermal loss characterization procedure and post processing the data has since been modified to improve accuracy of the net heat input calculation. As a result, the net heat input for all ASC-E2s is still being reviewed.

Following insulation loss characterization, #2 underwent performance mapping. The goal of this test was to duplicate the operating conditions achieved by Sunpower during the #2 final performance test. To accomplish this, the hot-end, CSAF, and alternator housing thermocouples were used as controlled parameters for repeating temperature conditions. Since too much uncertainty existed in the measurement of the piston amplitude as calculated from the ILS waveform, the alternator output voltage was instead used to attain the approximately same piston amplitude. The piston amplitude was calculated using the ILS signal and recorded in the data, but it was not used by the operator to set the convertor operating point. Also, uncertainty existed in the method of calculating net heat input both in the Sunpower and GRC test setups, so the net heat input was not used to control operation either. The hot-end thermocouples were adjusted using constant temperature control. No constant heater power method was used for this test. The CSAF thermocouple readings were adjusted by means of the cold-end circulator setpoint. The alternator housing thermocouple reading was adjusted by means of the alternator housing circulator setpoint. For some conditions, additional heat was applied to the alternator housing via the surface heaters. The alternator voltage was adjusted by means of the AC power supply voltage setpoint.

The results of the performance map are shown in Table 2. Also listed are the results from the Sunpower final performance test and the values from the product specification for comparison. All controlled temperatures were reproduced within 2 °C. The power output (at the connector) measured during GRC operation was within 1.5 percent of that measured during Sunpower operation for all conditions. The power output at the connector during GRC operation was greater than operation at Sunpower for the cases of Fueling, BOM High, and EOM High. For the other cases (BOM Low and EOM Low), power output was lower. These discrepancies may be explained by differences in piston amplitude or differences in achieving steady-state. The alternator connector voltage readout fluctuated by at least 0.1 V_{rms}, thus duplicating each alternator connector voltage in the Sunpower data set had some inherent imprecision. Some of the voltages differed by 0.2 V_{rms} (e.g., BOM Low). Since alternator output voltage is proportional to piston amplitude at a given operating condition, a lower voltage indicates lower piston amplitude. The power at the connector measured during GRC operation at the EOM Low condition was 0.6 percent (0.4 W_e) less than the product specification requirement. At the same conditions, the calculated power at the feedthrough terminals was 0.1 W_e lower than the specification. However, this was most likely due to the aforementioned imprecision in reproducing the operating conditions. At this point, the connector voltage was 1.2 percent lower than Sunpower's. Accordingly, the alternator current was 0.7 percent lower. Had the voltage been reproduced more precisely, the power output would have met the power output specification. Performance at all other operating conditions met or exceeded the product specification for power output.

Performance mapping was completed on April 15, and operation then transitioned to extended mode, during which the goal was to accumulate 500 hr at the BOM Low condition. #2 actually accumulated over 2400 hr of operation at this condition before it was manually shut down. Performance mapping and the majority of extended operation was at a hot-end temperature of 850 °C, which makes #2 the convertor with the most time at full temperature to date. However, future convertor operation will accumulate tens of thousands of hours of operation, for which the heat source is still yet to be proven capable. During #2's extended operation, other tests were performed at the request of Lockheed Martin that deviated from the BOM Low condition. There was no 500-hr span of operation where BOM Low was uninterrupted. The #2 power output during one particular 500-hr span of operation (May 4 to 25) is shown in Figure 4. The periods during which other tests were performed are shaded in the figure. The data in the shaded region can be ignored and do not represent changes in convertor performance, but rather manual adjustments to the operating conditions. The data outside the shaded region show negligible change in convertor power output from beginning to end of the 500-hr time span.

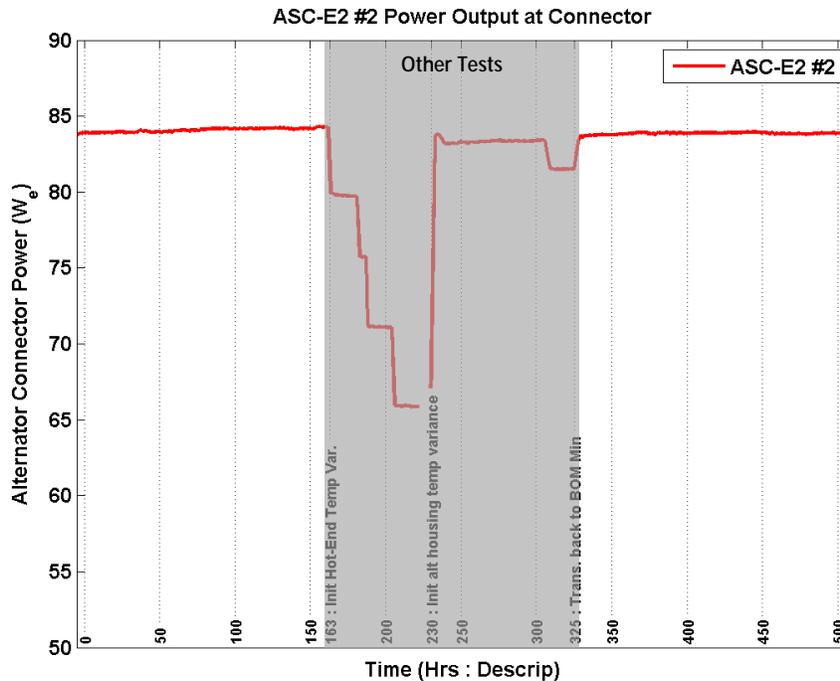


Figure 4.—ASC-E2 #2 power output over a 500-hr window of operation at BOM low.

Following extended operation, #2 was shut down and paired with #1 for electromagnetic interference (EMI) characterization. EMI testing was completed by mid-August. As of January 2011, #2 has accumulated over 2700 hr of runtime. #2 is scheduled to continue extended operation.

ASC-E2 #1

The second ASC-E2 (serial number 1) completed workmanship vibration testing on April 8, 2010, and was delivered to GRC on April 22. Installation of #1 onto the test station was completed by May 28. The thermal insulation loss characterization method was revised for #1. In this case, a thermal barrier was placed between the heat source and the convertor to effect the same temperature difference that exists when the convertor is operating. The goal of this effort was to raise the heat source to the same temperature as that when operating a convertor at 850 °C and improve the accuracy of the thermal loss characterization. From previous operational data, it was known that the heat source temperature reaches as high as 1000 °C to operate a convertor at 850 °C and maximum power flow. However, as of date the calculation of net heat input is still being reviewed. Following thermal loss characterization, the thermal barrier was removed and replaced by the diffusion-preventing alumina disk.

#1 began performance mapping on June 17, 2010. The test procedure was the same as that used for #2. The results of the performance mapping test are listed in Table 2. All controlled temperatures were reproduced within 2 °C of the target. The power output (at the connector) measured during operation at GRC was between 1.4 and 6.3 percent greater than that measured during Sunpower operation for all conditions. However, the alternator leads were shortened after delivery to GRC. The lead length was reduced from 36 to 28 in. It has been estimated that because of this, the lead resistance was reduced from 42 to 32.7 mΩ. Thus, a higher power output at the connector would be measured in the case of the shorter leads. A more accurate comparison of power output could be made by comparing the calculated feedthrough power, which neglects the power loss through the alternator leads. Using this, the convertor power output measured during GRC testing was within 2.5 percent of Sunpower's values in all cases

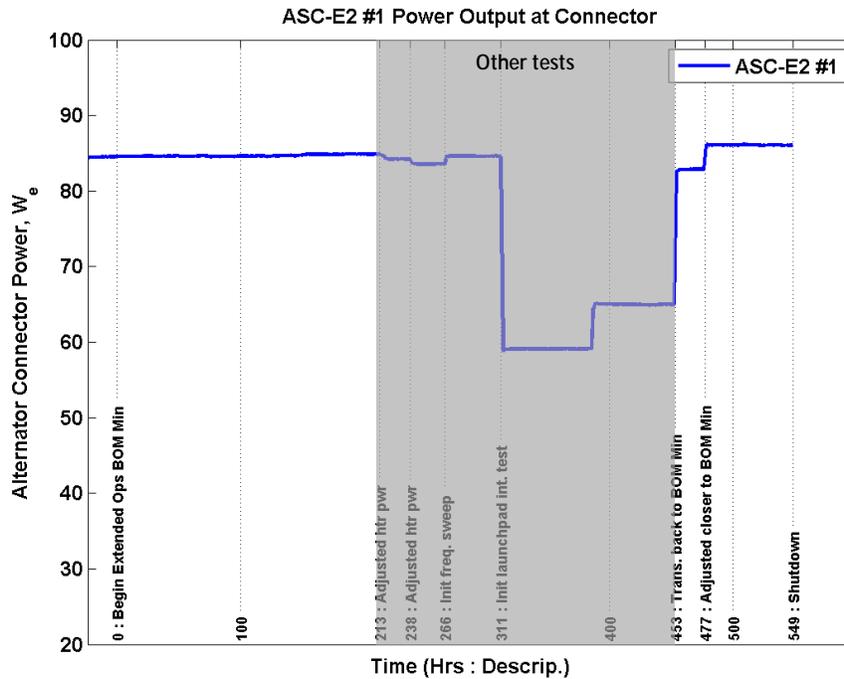


Figure 5.—ASC-E2 #1 power output over a 500-hr window of operation at BOM low.

except EOM Low. For EOM Low, the feedthrough power measured at GRC was 5.2 percent greater. This outlier could be explained by the fact that the alternator output voltage was not matched as precisely as the other operating points. For EOM Low, the alternator connector voltage was 0.7 percent higher, and the piston amplitude was 1.7 percent higher. For all other operating points, the alternator connector voltage was matched to Sunpower’s values within 0.5 percent. The convertor power output met or exceeded the product specification requirement for all operating conditions.

Performance mapping of #1 was concluded on July 1 and extended operation at BOM Low was initiated the same day. Operation was continuous until a manual shut down was initiated on July 26, at which time the cumulative runtime totaled 889 hr. A plot of #1’s power output during a 500-hr window of extended operation is shown in Figure 5. Manual adjustments were made to maintain the operating condition setpoints at hour markers 213, 238, and 477. The step changes seen at these points do not represent changes in convertor performance. These adjustments were made to account for changes in heat source hardware and high-temperature insulation during the first 200 hr of extended operation, and following a set of supplementary tests. Between the hours of 266 and 453 (shaded in the plot), other tests were performed. The data here do not represent convertor operation at BOM Low. The data show steady convertor output outside the shaded region and in between manual operating condition adjustments.

Following extended operation, #1 was shut down and paired with #2 for EMI testing. #1 has since then begun operation with a “compact” heat source that does not protrude through the insulation like the HT Firerod cartridges. The goal of this is to reduce the losses from the heater to the environment and to obtain a more accurate calculation for net heat input. Following this activity, #1 is scheduled to be paired with #2 and continue extended operation in the dual-opposed horizontal configuration. As of January 2011, #1 has accumulated 2600 hr of runtime.

ASC-E2 #3 and #4

The second pair of ASC-E2 converters, #3 and #4, was delivered to GRC on April 28, 2010. Since the converters were delivered together, they were assembled in the dual-opposed vertical configuration (Figure 6). This configuration was chosen to emulate the orientation of the ASRG EU currently undergoing extended operation. Shown in the figure is the final converter assembly for operation. As such, all converter surfaces are shown insulated. Thermal insulation loss characterization was completed in the same fashion as that described for #1. The thermal barrier was used to elevate the heat source temperature to simulate an operating temperature profile. Performance mapping was performed from July 12 through 17. A total of 10 operating points were achieved even though there are seven operating conditions called out in the product specification. This is because in the dual-opposed configuration with a single AC bus controller, some points could not be achieved on both converters simultaneously. In these cases, the conditions were achieved for one converter, while deviating slightly on the other, and vice versa. The performance data gathered at GRC matched well with Sunpower's data (Table 2). As was true for the first two ASC-E2s, some points differ due to imprecision associated with duplicating operation based on alternator connector voltage, and data acquisition methods.

Extended operation at BOM Low began at the conclusion of the performance mapping on July 17 and lasted until August 8. Data from extended operation are still being assembled, and will be covered in future publications. Following extended operation, the converters were shipped to Lockheed Martin and are being used for controller development. As of January 2011, ASC-E2 #3 and #4 have each accumulated 840 hr of runtime.

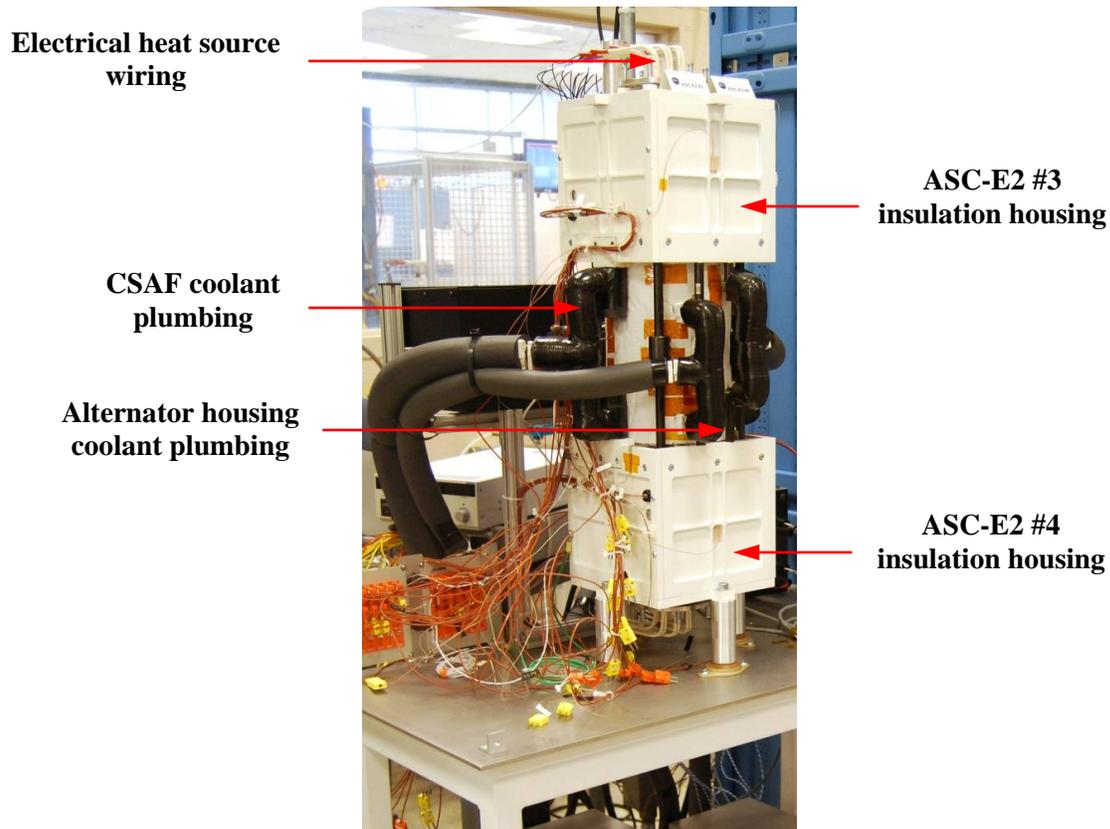


Figure 6.—ASC-E2 #3 and #4 assembled in the dual-opposed vertical configuration.

ASC-E2 #5 and #6

The third pair of ASC-E2 convertors, #5 and #6, completed workmanship vibration testing on July 7, 2010 and was delivered to GRC on July 23. These convertors have completed performance mapping, which began in October 2010, as well as 500 hr of extended operation at BOM Low. The performance data for these tests are still being assembled and analyzed. As of January 2011, these convertors have each accumulated 1,970 hr of runtime.

ASC-E2 #7 and #8

The fourth pair of convertors, #7 and #8, was delivered to GRC on August 13, 2010. #7 was operated in the single vertical configuration and completed performance mapping. The performance mapping data are still being assembled and analyzed. This convertor is currently undergoing 500 hr of extended operation at BOM Low. #8 was returned to Sunpower for supplementary testing support and will be returned to GRC in the near future.

These convertors will also be used for durability testing, during which some components may be stressed beyond nominal conditions. Figure 7 shows the removable alternator housing installed on these convertors to allow for inspection of internal components after each test. In contrast, convertors #1 through #6 were fabricated with hermetically sealed alternator housings. The purpose of the durability tests is to experimentally demonstrate the margins that exist in the ASC-E2 design. The durability tests will subject the convertors to conditions beyond those intended to meet the product specification. During these tests, the possibility exists of axial or lateral contact, piston contact events, and over-temperature. These tests are not designed to result in damage that would significantly shorten convertor life, such that the convertors may later be hermetically sealed and continue extended operation. Table 1 summarizes the planned tests.



Figure 7.—ASC-E2 #7 and #8 with removable alternator housings for inspection after durability testing.

TABLE 1.—SUMMARY OF PLANNED ASC-E2 #7 AND #8 DURABILITY TESTING

Test description	Purpose	Anticipated date
Start/Stop cycling	Cycle the convertor repeatedly through start/stop cycle to exacerbate any possible wear induced before gas bearings become fully functional	March 2011
Contact events during launch	Simulate a limited number of contact events during launch by adjusting piston amplitude	April 2011
Piston overstroke	Simulate a limited number of contact events with desired relative velocities between the piston and displacer by adjusting piston amplitude	May 2011
Centrifugal acceleration	Expose operating convertor to 30 g static load using a centrifuge facility to observe response in moving components	June 2011

ASC-E2 #1 Through #4 Performance Comparison

For simplicity, the results of performance mapping for the first four convertors (#1 through #4) are contained in Table 2. #1 and #2 were operated as single units, each in the vertical orientation with the heater head in the upwards direction. #3 and #4 were operated as a pair in the dual-opposed vertical configuration, which emulates ASRG engineering unit operation (Ref. 2). Prior to delivery, Sunpower operated each convertor individually at each of the points shown in the table. For comparison to Sunpower’s operation, the convertors were each operated at GRC by duplicating the temperatures and alternator connector voltages for each operating point. All temperatures were duplicated within 2 °C. The connector voltages were each duplicated within less than 1.4 percent, due to imprecision associated with adjusting alternator voltage via the aforementioned method. With this, individual convertor power output differed by 3 percent or less between Sunpower and GRC data, except for EOM Low on ASC-E2 #1. This outlier is most likely due to higher operating point duplication discrepancy. The GRC EOM Low data point for #1 was at a higher piston amplitude than Sunpower’s data point, resulting in a higher power output. Other discrepancies may be accounted for by differences in data recording and averaging techniques at the two laboratories. As of writing, both the method for performing thermal insulation loss characterization and the calculation of net heat input are being scrutinized and refined. The results of this effort will be summarized in future publications. The current method for calculating net heat input at GRC yields convertor efficiencies between 32 and 38 percent across all the operating cases shown in the table. If examining the unit-to-unit repeatability, the available data show that the standard deviation in power output is less than two W_e for each of the operating cases shown here. An unknown portion of this variability is due to imprecision in repeating a given operating point.

TABLE 2.—SUMMARY OF ASC-E2 #1, #2, #3, AND #4 PERFORMANCE MAPPING AT SUNPOWER AND GRC

ASC-E2 #1, #2, #3, #4	Acceptor Temp	Rejector Temp	Alternator Housing Temp	Frequency	Power Output Feedthroughs	Power Output Connector	Alt Voltage Connector
Units -->	°C (calc)	°C (calc)	°C (meas)	Hz (meas)	W _e (calc)	W _e (meas)	V _{rms} (meas)
Measurement Uncertainty -->	± 1	± 1	± 2		± 0.47	± 0.47	± 0.04
Fueling Spec	850	98 ±2	104 ±2	102.2 ±0.2	Safe operation	Safe operation	10.3 to 18.3
#1 Sunpower	849	98	104	102.2	81.1	76.9	14.71
GRC	850	98	104	102.2	82.1	78.7	14.71
#2 Sunpower	850	98	104	102.2	80.8	76.0	15.81
GRC	849	99	104	102.2	81.6	76.7	15.81
#3 Sunpower	849	99	104	102.2	80.4	75.6	16.12
GRC	849	99	104	102.2	78.6	73.6	16.19
#4 Sunpower	848	99	103	102.2	80.9	76.2	15.82
GRC	848	99	104	102.2	78.4	73.6	15.90
Standard Dev.	1	1	0	0	1.3	1.7	0.6
BOM Low Reject Spec	≤ 850	52 ±2	61 ±2	102.2 ±0.2	≥ 84.5	≥ 80.9	10.3 to 18.3
#1 Sunpower	848	51	62	102.2	85.6	81.7	13.29
GRC	850	52	61	102.2	87.4	84.3	13.29
#2 Sunpower	849	52	61	102.2	86.1	82.0	14.32
GRC	849	52	59	102.2	85.5	81.5	14.13
#3 Sunpower	850	53	62	102.2	85.5	81.6	14.55
GRC	849	51	62	102.2	86.6	82.5	14.65
#4 Sunpower	849	52	61	102.2	85.3	81.5	14.25
GRC	850	52	61	102.2	83.6	79.8	14.11
Standard Dev.	1	0	1	0	1.1	1.3	0.5
BOM High Reject Spec	≤ 850	90 ±2	98 ±2	102.2 ±0.2	≥ 79.5	≥ 75.7	10.3 to 18.3
#1 Sunpower	848	90	99	102.2	80.2	76.1	14.39
GRC	849	90	99	102.2	81.5	78.2	14.46
#2 Sunpower	850	91	98	102.2	80.7	76.1	15.51
GRC	849	90	98	102.2	81.3	76.7	15.50
#3 Sunpower	848	90	98	102.2	80.5	75.9	15.83
GRC	848	89	97	102.2	80.9	76.1	15.98
#4 Sunpower	846	90	98	102.2	81.2	76.7	15.60
GRC	846	90	98	102.2	80.1	75.5	15.67
Standard Dev.	1	0	0	0	0.5	0.8	0.6
EOM Low Reject Spec	≤ 850	36 ±2	44 ±2	102.2 ±0.2	≥ 75.3	≥ 72.2	10.3 to 18.3
#1 Sunpower	851	36	45	102.2	76.3	72.9	12.03
GRC	850	37	45	102.2	80.3	77.5	12.12
#2 Sunpower	849	37	44	102.2	76.4	72.9	12.91
GRC	849	36	44	102.2	75.2	71.8	12.76
#3 Sunpower	850	36	44	102.2	76.0	72.8	13.05
GRC	850	36	44	102.2	75.6	72.6	12.98
#4 Sunpower	848	38	44	102.2	76.0	72.8	12.89
GRC	847	37	44	102.2	77.5	74.1	12.96
Standard Dev.	1	1	0	0	1.6	1.8	0.4
EOM High Reject Spec	≤ 850	90 ±2	98 ±2	102.2 ±0.2	≥ 69.2	≥ 65.9	10.3 to 18.3
#1 Sunpower	849	90	98	102.2	69.6	66.0	13.39
GRC	850	90	98	102.2	70.6	67.8	13.41
#2 Sunpower	848	90	98	102.2	70.2	66.1	14.49
GRC	849	90	98	102.2	71.0	66.9	14.50
#3 Sunpower	848	90	97	102.2	70.3	66.3	14.77
GRC	848	90	96	102.2	70.2	66.1	14.87
#4 Sunpower	845	90	97	102.2	70.1	66.3	14.51
GRC	845	90	97	102.2	69.5	65.6	14.58
Standard Dev.	2	0	1	0	0.5	0.7	0.6

Conclusions

For the purpose of generating life and reliability data for the ASRG project, NASA GRC has begun operating several ASC-E2 units. Table 3 summarizes the ASC-E2 activity as of January 2011. Seven of the eight convertors have begun operating. Over 12,000 hr of operation have been accumulated on these seven ASC-E2s. Data indicated convertor performance at GRC and Sunpower matched well, with differences less than 3 percent. Discrepancies in measured performance were accounted for by differences in operating conditions, and did not indicate changes in convertor performance. Data from a 500-hr window of operation at BOM Low were analyzed for two convertors (#1 and #2). These data showed steady performance over this timespan. The remaining convertor performance data will be covered in future publications.

TABLE 3.—SUMMARY OF ASC-E2 TESTING AT GRC AS OF JANUARY 2010

Convertor	Cumulative runtime, hr	Status
ASC-E2 #1	2600	Extended operation
ASC-E2 #2	2700	Extended operation
ASC-E2 #3 and #4	840	Controller development at Lockheed Martin
ASC-E2 #5 and #6	1970	Extended operation
ASC-E2 #7	1150	Extended operation
ASC-E2 #8	0	Supplementary test support at Sunpower
Total = 12,070 hr		

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14. ABSTRACT The National Aeronautics and Space Administration (NASA) Glenn Research Center (GRC) has been supporting development of the Advanced Stirling Radioisotope Generator (ASRG) since 2006. A key element of the ASRG Project is providing life, reliability, and performance testing of the Advanced Stirling Convertor (ASC). For this purpose, four pairs of ASCs capable of operating to 850 °C and designated with the model number ASC-E2, were delivered by Sunpower of Athens, Ohio, to GRC in 2010. The ASC-E2s underwent a series of tests that included workmanship vibration testing, performance mapping, and extended operation. Workmanship vibration testing was performed following fabrication of each convertor to verify proper hardware build. Performance mapping consisted of operating each convertor at various conditions representing the range expected during a mission. Included were conditions representing beginning-of-mission (BOM), end-of-mission (EOM), and fueling. This same series of tests was performed by Sunpower prior to ASC-E2 delivery. The data generated during the GRC test were compared to performance before delivery. Extended operation consisted of a 500-hr period of operation with conditions maintained at the BOM point. This was performed to demonstrate steady convertor performance following performance mapping. Following this initial 500-hr period, the ASC-E2s will continue extended operation, controller development and special durability testing, during which the goal is to accumulate tens of thousands of hours of operation. Data collected during extended operation will support reliability analysis. Performance data from these tests is summarized in this paper.					
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