

Advanced Stirling Convertor Testing at NASA Glenn Research Center

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The NASA Glenn Research Center (GRC) has been testing high-efficiency free-piston Stirling convertors for potential use in radioisotope power systems (RPSs) since 1999. The current effort is in support of the Advanced Stirling Radioisotope Generator (ASRG), which is being developed by the U.S. Department of Energy (DOE), Lockheed Martin Space Systems Company (LMSSC), Sunpower, Inc., and the NASA GRC. This generator would use two high-efficiency Advanced Stirling Convertors (ASCs) to convert thermal energy from a radioisotope heat source into electricity. As reliability is paramount to a RPS capable of providing spacecraft power for potential multi-year missions, GRC provides direct technology support to the ASRG flight project in the areas of reliability, convertor and generator testing, high-temperature materials, structures, modeling and analysis, organics, structural dynamics, electromagnetic interference (EMI), and permanent magnets to reduce risk and enhance reliability of the convertor as this technology transitions toward flight status. Convertor and generator testing is carried out in short- and long-duration tests designed to characterize convertor performance when subjected to environments intended to simulate launch and space conditions. Long duration testing is intended to baseline performance and observe any performance degradation over the life of the test. Testing involves developing support hardware that enables 24/7 unattended operation and data collection. GRC currently has 14 Stirling convertors under unattended extended operation testing, including two operating in the ASRG Engineering Unit (ASRG-EU). Test data and high-temperature support hardware are discussed for ongoing and future ASC tests with emphasis on the ASC-E and ASC-E2.

Nomenclature

<i>ACU</i>	=	Advanced Stirling Convertor Controller Unit
<i>ASC(-EU)</i>	=	Advanced Stirling Convertor (for the Engineering Unit)
<i>ASRG(-EU)</i>	=	Advanced Stirling Radioisotope Generator (Engineering Unit)
<i>BOM</i>	=	Beginning of Mission
<i>CSAF</i>	=	Cold-Side Adapter Flange
<i>DOE</i>	=	Department of Energy
<i>EMI</i>	=	Electromagnetic Interference
<i>EOM</i>	=	End of Mission
<i>FLDT</i>	=	Fast Linear Displacement Transducer
<i>GRC</i>	=	Glenn Research Center
<i>HT</i>	=	High-Temperature
<i>LMSSC</i>	=	Lockheed Martin Space Systems Company
<i>RPS</i>	=	Radioisotope Power System
<i>TDC</i>	=	Technology Demonstration Convertor

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I. Introduction

STIRLING power conversion technology is being developed for space flight by the U.S. Department of Energy (DOE), Lockheed Martin Space Systems Company (LMSSC), Sunpower, Inc., and the NASA Glenn Research Center (GRC). NASA GRC has been testing high-efficiency free-piston Stirling convertors for potential use in radioisotope power systems (RPSs) since 1999. The current effort is in support of the Advanced Stirling Radioisotope Generator (ASRG) which has demonstrated significantly higher system efficiency in comparison to radioisotope thermoelectric generators, reducing the amount of fuel (Pu238) required by a factor of four. Reliability of the power system is paramount to the ASRG and the Advanced Stirling Convertors (ASC). GRC provides direct technology support to the DOE/LMSSC ASRG flight project in the areas of reliability, convertor and generator testing, high-temperature materials, structures, modeling, and analysis, organics, structural dynamics, electromagnetic interference (EMI), and permanent magnets. The project utilizes GRC resident experts on tasks intended to reduce risk and enhance reliability of the convertor as this technology transitions toward flight status.

Convertor and generator testing is carried out in short- and long-duration tests designed to characterize convertor performance when subjected to environments intended to simulate launch and space conditions. Short duration tests include random vibration, thermal vacuum, and EMI testing as well as other special tests.¹ Long duration tests are intended to baseline performance and quantify performance degradation over the life of the convertor. Testing involves developing support hardware that enables 24/7 unattended operation and data collection, including control and data acquisition systems, heating and cooling components, and general mounting and insulation packages. GRC currently has 14 Stirling convertors under unattended extended operation testing including two operating in the ASRG Engineering Unit (ASRG-EU). Test stations are being prepared for four additional ASC-E2s, which are expected to undergo testing at GRC later this year.

II. ASC-E and ASC-E2 Testing at GRC

The ASC was designed and fabricated by Sunpower, Inc., under contract to NASA GRC. It was designed to produce a nominal 80 We from 250 W_{th} gross heat input when integrated into a generator. The ASC-E convertors utilize Inconel 718 heater heads while the ASC-E2 convertors utilize MarM-247 heater heads, which operate at a maximum hot-end temperature of 650 and 850 °C, respectively. The cold-end temperature operating range is 40 to 90 °C for the ASC-E. The operating range has been expanded significantly to 15 to 124 °C for the ASC-E2. A heat collector is attached to the hot end of the heater head, which interfaces to an electric heat source during laboratory operation. A conductive flange called the cold-side adapter flange has been attached to the heat rejection zone of the heater head that allows attachment of cooling loops.

The ASC-E design has been refined into the ASC-E2, and will be refined to the ASC-E3 after all of the E2 convertors have been delivered later this year. The intent behind the progressive build sequence is to minimize design changes through this progression toward flight, with refinements only for manufacturing, quality, and process control. All of these efforts seek to minimize risk and enhance reliability as the ASC transitions to flight.

There are several types of tests planned for the eight ASC-E2s including extended operation, durability, and accelerated life tests. Extended operation testing of convertors at nominal operating conditions is intended for monitoring performance over time. Durability testing is intended to provide reliability data that demonstrates the long term reliability and robustness of the ASCs. The durability tests include start/stop cycles, launch over-stroke test, controller over-stroke test, and +30 g static acceleration test, all of which will test the convertors beyond their nominal operating range out in the design margin and not intended to cause permanent damage. Accelerated life tests include higher than nominal temperature and higher than nominal piston amplitude and are also designed to test the convertors beyond their nominal operating range in the design margin, providing data to demonstrate convertor reliability for long-term missions. Table I summarizes ongoing ASC-E and ASC-E2 testing as well as planned testing for 2010 and 2011. The convertor pair, test environment, controller type, operating temperatures used during extended operation, initiation date, run times through June 2010, and status are shown. Controller testing is planned for ASC-E2 #2, #3, and #4. Operating conditions selected for extended operation are those specified in the performance map test matrix as beginning-of-mission low rejection temperature (BOM-LR). Testing of ASC-E2 #5, #6, #7, and #8 is expected to begin later this year.

In addition, a pair of ASC-E2 convertors will be used for controller development at Lockheed Martin, allowing researchers to test controllers on convertors for which they were designed.

Table I. Current and Future ASC-E and ASC-E2 Testing at GRC

Convertor	Testing environment	Control	Ext. Operating Temperatures (Thot/Tcold) °C	Date operation initiated	Hours	Status
ASC-E #2 and #3	In air, ASRG enclosure w/ argon, workmanship, qualification level vibration, EMI, thermal vacuum	AC Bus, ACU	625/60	Oct 2008	11500	Ongoing test
ASC-E #1 and #4	In air, workmanship, launch simulation on ASC-E #1 only	AC Bus (ACU planned)	625/70	Dec 2009	4400	Ongoing test
ASC-E2 #1	In air, workmanship, single configuration	AC Bus	850/50	May 2010	400	Ongoing test
ASC-E2 #2	In air, workmanship, single configuration	AC Bus, (ACU planned)	850/50	Mar 2010	2000	Ongoing test
ASC-E2 #3 and #4	In air, workmanship, dual-opposed configuration	AC Bus, (ACU planned)	850/50	July 2010	100	Ongoing test
ASC-E2 #5 and #6	<i>In air, workmanship, dual-opposed configuration, accelerated life tests planned</i>	<i>AC Bus planned</i>	<i>850/50 planned</i>	n/a	n/a	<i>Future test</i>
ASC-E2 #7 and #8	<i>In air, workmanship, dual-opposed configuration, durability tests planned</i>	<i>AC Bus planned</i>	<i>850/50 planned</i>	n/a	n/a	<i>Future test</i>

III. High-Temperature Support Hardware

Support hardware was developed to provide proper heating and cooling of the convertor. Electric heaters and fluid cooling loops are used to control the temperatures of the hot and cold ends of the Stirling convertor. The test rack provides means for data collection and test setup controls for setting the operating point by adjusting the heat source power input, fluid circulator set point, and piston amplitude. The test rack also provides safeguards by triggering a controlled shutdown in the event of a facilities failure, such as a power outage, or an instrumentation failure on a sensor required to control the operating point.² As the convertor design transitioned from the ASC-E, which has an Inconel heater head to the ASC-E2 that has a MarM heater head, the convertor hot-end temperature increased from 650 to 850 °C. The electric heat source temperature required to maintain the 850 °C hot-end temperature in ground tests increased as well, approaching 1000 °C. This proved to be problematic with standard cartridge heaters because they were not rated for operation above 760 °C. As such, the heat sources typically only lasted a few hundred hours, which delayed testing of convertors at the desired conditions. To enable long-duration 850 °C convertor tests, a high-temperature heat source development activity was initiated. In addition to heat source development, the insulation package was redesigned to minimize heat loss from the heat source to the environment during operation.

A. Heater Development

A heat source development activity was initiated to identify a suitable option for long-duration 850 °C convertor tests. This activity identified four possibilities that offered potential improvement over standard cartridge heat sources used in the lab for past convertor operation. The four products considered were 1) Watlow High-Temperature (HT) Firerod cartridges, 2) Dalton Electric Wattflex cartridges, 3) Momentive Boralectric heaters with plated contacts, and 4) Kanthal Superthal radiant heater. Each option was evaluated via bench testing. The first three listed options were driven to failure during bench testing, while the Kanthal Superthal bench test was terminated before any failure occurred. The Boralectric heater with platinum-plated contacts did not survive the initial heat up to the operating temperature. The Wattflex cartridge option survived for only 375 hr at 1075 °C and 270 W of electrical power input. The HT Firerod cartridge option survived for 1400 hr at 1075 °C and 300 W of electrical power input. The cartridges were tested at a higher temperature than they will see in use to accelerate the test. The Kanthal Superthal radiant heater was operated for 1,500 hours at a heat collector face temperature of 950 °C and 400 W of electrical power input with no evidence of aging or degradation.

The Kanthal Superthal radiant heater offers several advantages over a conductively coupled heater since it eliminates the need for constraint mechanisms, such as fasteners and spring loading devices, which provide the

coupling force required to hold the heat source to the convertor's heat collector but also introduce a conduction path between the heat source and the outside environment. The Kanthal Superthal radiant heater also avoids disadvantages of thermal contact resistance and diffusion bonding between the conductively coupled heat source and the convertor.

Based on initial test results, an improved HT Firerod cartridge heater was designed. The improved HT Firerod cartridges and the Kanthal Superthal radiant heaters will be used for most ASC-E2 testing. The HT Firerod cartridges are being used on the first four ASC-E2 tests due to availability of hardware. The HT Firerod cartridge heaters have operated for over 2000 hr on ASC-E2 #2 testing at a heat source temperature of 975 °C without any evidence of degradation. Plans are in place to implement radiant heating for long-term ASC-E2 operation at 850 °C. Figure 1 shows the Kanthal Superthal radiant heater and the HT Firerod heat source.

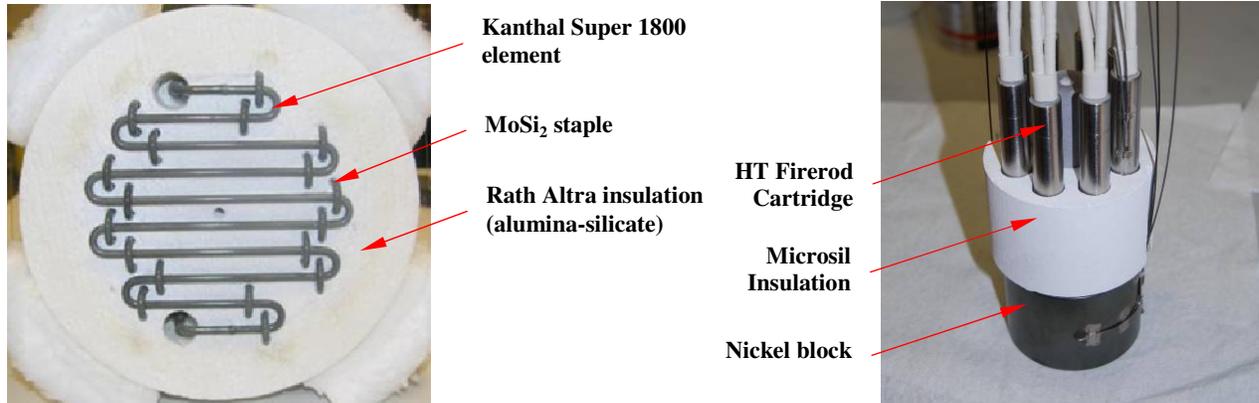


Figure 1. Kanthal Superthal 1800 heating element assembly (left) and Firerod Cartridge Heater (right). The serpentine-shaped MoSi₂ element of the Kanthal Radiant heater is attached to the solid insulation with staples also made of MoSi₂.

B. Insulation for 850 °C Operation

The insulation enclosure is used for mounting the convertor and many test components including the heat source, cooling plumbing, and bulk insulation. The enclosures, machined from aluminum, have been designed to the representative size and general shape of the ASRG-EU housing (see Fig. 3). The enclosures house the Microsil microporous insulation used to minimize heat loss from the heat source to the environment during operation. The insulation package is made of several different types of insulation including microporous insulation, ceramic paper, and Kaowool™ blanket insulation. Figure 2 shows the different areas where each type of insulation was used and how the heat source locates against the hot end of the Stirling convertor heater head (labeled ASC-E2 Head). The heat source is spring loaded against the convertor heater head using a Cotronics Rescor ceramic load stud, which has a temperature limit of 1150 °C. Heat source temperatures can exceed 1000 °C when operating with an 850 °C hot-end temperature. The Microsil microporous insulation has a temperature limit of 1000 °C, so the Kaowool blanket and ceramic paper insulations, which have a temperature limit of above 1100 °C were used to separate the Microsil from heat source. Thermocouples were located inside the test setup to monitor internal temperatures and gather data for thermal modeling tasks. Figure 3 shows ASC-E2 #4 during different stages of the support hardware assembly. The leftmost image shows the heat source, bulk insulation, and thermocouples installed.

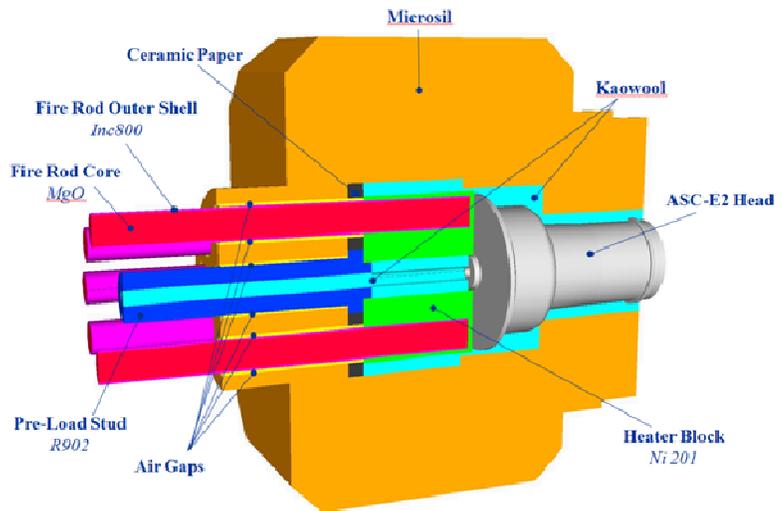


Figure 2. ASC-E2 Microporous insulation package.

The center image shows the blanket insulation installed and the rightmost shows the enclosure walls and load mechanism assembled. Each convertor assembly is mounted in dual-opposed configuration which is then anchored on the test stand table. The ASC-E #1 and #4 and ASC-E2s use similar support hardware.

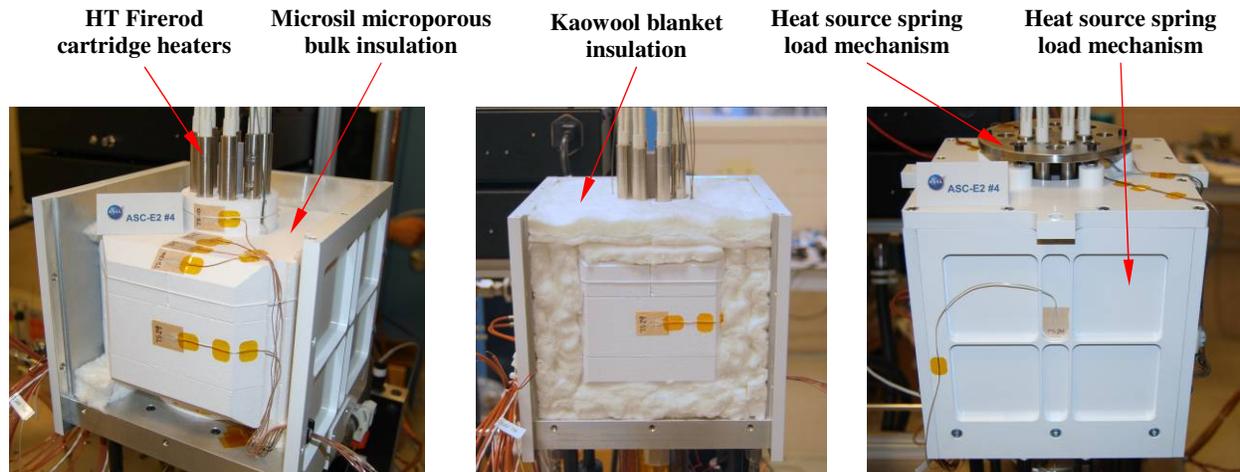


Figure 3. Insulation package for ASC-E2 testing. ASC-E2 #4 shown.

C. ASRG-EU (ASC-E #2 and #3)

The ASRG-EU was designed and fabricated by LMSSC under contract to the DOE. It contains ASC-E #2 and #3 and an ASC Controller Unit (ACU) mounted to the outside of the housing. The ASRG-EU completed a variety of tests at the LMSSC facility before delivery to GRC. Tests included thermal performance in a vacuum chamber, mechanical disturbance, sine transient, random vibration, shock, and EMI.³ The ASRG-EU was operated for a total of 1124 hr at LMSSC before delivery to GRC on August 28, 2008. The ASRG-EU was initially operated under alternating current (AC) bus control to characterize performance of the engineering unit and the test facility independent of the ACU. Extended operation under AC bus control commenced on November 6, 2008. The ASRG-EU has been operated at a hot-end temperature of 625 °C on both convertors, while the average rejection temperature was about 68 °C for the convertors. Improvements to the cooling system have reduced the rejection temperature to about 63 °C.³ The ASRG-EU began extended operation under ACU control in June 2009 and has accumulated over 5600 hr of operation under ACU control.

Figure 4 shows performance data for extended operation through 10,500 hr. Fluctuations in output power, while operating under AC bus control, were due to variation in test rack wiring impedance. Changes in performance while operating under ACU control are due to manual changes in set points and test parameters as driven by the need to perform short-duration tests for ASRG development.⁴ The ASRG-EU has operated to date with no measurable change in convertor performance.

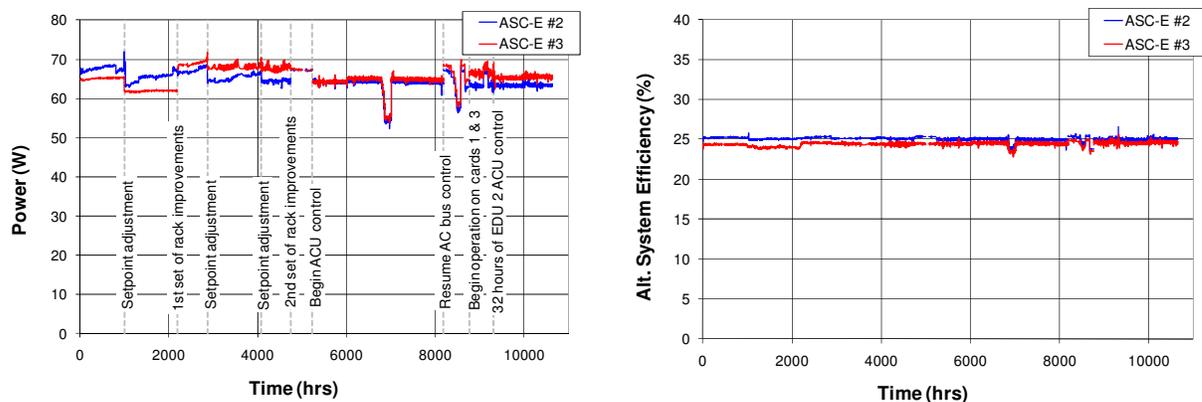


Figure 4. Power output and efficiency performance data from ASRG-EU (ASC-E #2 and #3) through 10,500 hr of operation.

D. ASC-E #1 and #4

ASC-E #1 and #4 units, delivered to GRC in December 2008 and May 2009, respectively, began extended operation in December 2009. The ASC-E #1 is the spare convertor from the fabrication of the ASRG-EU, and the ASC-E #4 was built using spare components from the earlier ASC-E builds. These convertors were designed with Inconel 718 heater heads, which have 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.

Prior to beginning extended operation, ASC-E #1 was operated under ACU control as part of a controller vibration test. While operating on the ACU, vibration testing was carried on ASC-E #1 at launch conditions while the convertor was exposed to qualification level vibration in the axial direction and flight acceptance level vibration in the two lateral axes. ASC-E #4 was not tested under launch simulation conditions. Figure 5 shows power output and net efficiency to date for ASC-E #1 and #4. Fluctuations in performance are attributed to changes in room temperature. Figure 6 shows the test setup for ASRG-EU (left) and ASC-E #1 and #4 (right). Table II summarizes ASC-E average performance data for extended operation. ASC-E #2 and #3 data was averaged from 7400 to 8000 hr and ASC-E #1 and #4 data was averaged from 3400 to 4400 hr.

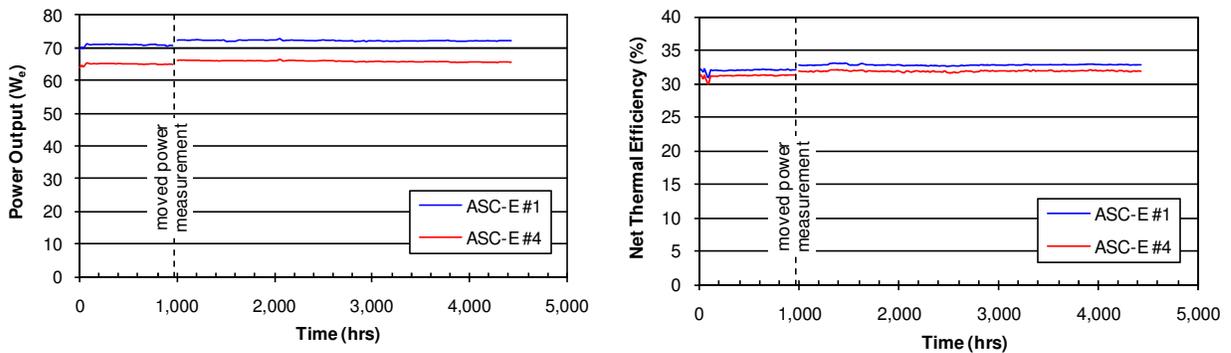


Figure 5. Power output and efficiency performance data from ASC-E #1 and #4 through 4300 hr of operation.

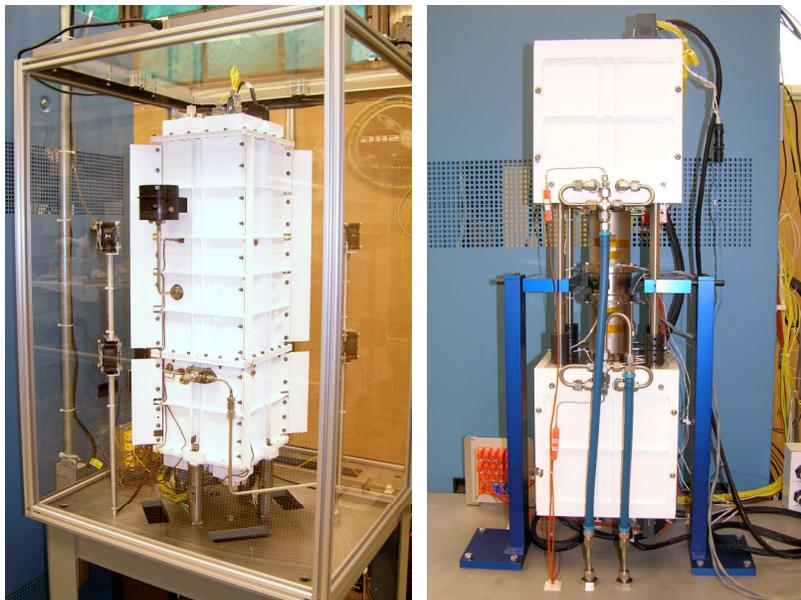


Figure 6. ASRG-EU containing ASC-E #2 and #3 (left) and ASC-E #1 and #4 (right).

Table II. Summary of ASC-E Extended Operation Data

Parameter	Units	ASC-E #2	ASC-E #3	ASC-E #1	ASC-E #4
		ASRG-EU		Dual-opposed configuration	
Average hot-end temperature	°C	623.7	623.9	626.3	626.1
Rejection temperature	°C	63.4	61.8	70.4	69.5
Alternator housing temperature	°C	66.7	65.6	65.8	68.0
Gross heat input	W_{th}	257	265	283	264
Net heat input	W_{th}	n/a	n/a	219	206
Gross efficiency	%	25.0	24.5	25.4	24.9
Net efficiency	%	n/a	n/a	32.9	31.9
Alternator voltage	V_{rms}	10.2	9.8	11.3	12.0
Alternator current	A_{rms}	8.0	8.4	8.5	7.7
Alternator power output	W_e	64.1	64.9	72.1	65.7
Piston amplitude	mm	4.23	4.25	4.31	4.19
Operating frequency	Hz	102.9	102.9	102.2	102.2

ASC-E #2 and #3 data averaged from 7400 to 8000 hr

ASC-E #1 and #4 data averaged from 3400 to 4400 hr

E. ASC-E2 #1 and #2

ASC-E2 #2 was delivered to GRC on February 5, 2010, and ASC-E2 #1 was delivered to GRC on April 22, 2010. ASC-E2 #2 underwent thermal loss characterization and performance mapping and began extended operation on May 4, 2010. ASC-E2 #2 has operated for over 2000 hr at a hot-end temperature of 850 °C. Thermal loss characterization was performed to be able to calculate thermal losses through the insulation and convertor efficiency. This test was performed by setting various steady hot-end and cold-side adapter flange (CSAF) temperatures on a nonoperating convertor while measuring heater power.

Performance mapping consisted of convertor operation at various thermal conditions expected during a mission. Included were conditions representing beginning of mission (BOM), end of mission (EOM), and fueling. Two CSAF temperatures (a minimum and a maximum) were used at each BOM and EOM cases. Also included in this test were conditions for minimum and maximum qualification. Throughout these test conditions the CSAF temperature was varied between 16 and 124 °C, while the alternator housing temperature was varied between 23 and 130 °C. ASC-E2 #2 met or exceeded test expectations for all points.

Extended operation of ASC-E2 #2 is currently in progress and consists of maintaining the BOM minimum CSAF temperature condition for at least 500 hr. Throughout extended operation, other tests have been performed on ASC-E2 #2 at the request of the system integrator. The periods during which these tests were being performed are shaded in Figure 7 and do not reflect changes in convertor performance. Before, after, and between these tests the convertor performance was identical within measurement accuracy. Other minor variances in power output can be attributed to fluctuations in the laboratory's ambient temperature. Also, the x-axis of Fig. 7 starts at approximately 600 hr, since the convertor operated for 570 hr during performance mapping before initiating extended operation.

Delivery of ASC-E2 #1 was delayed due to a fabrication defect identified late in the manufacturing process prior to delivery, but has since gone through thermal loss characterization and performance mapping and has recently begun extended operation.

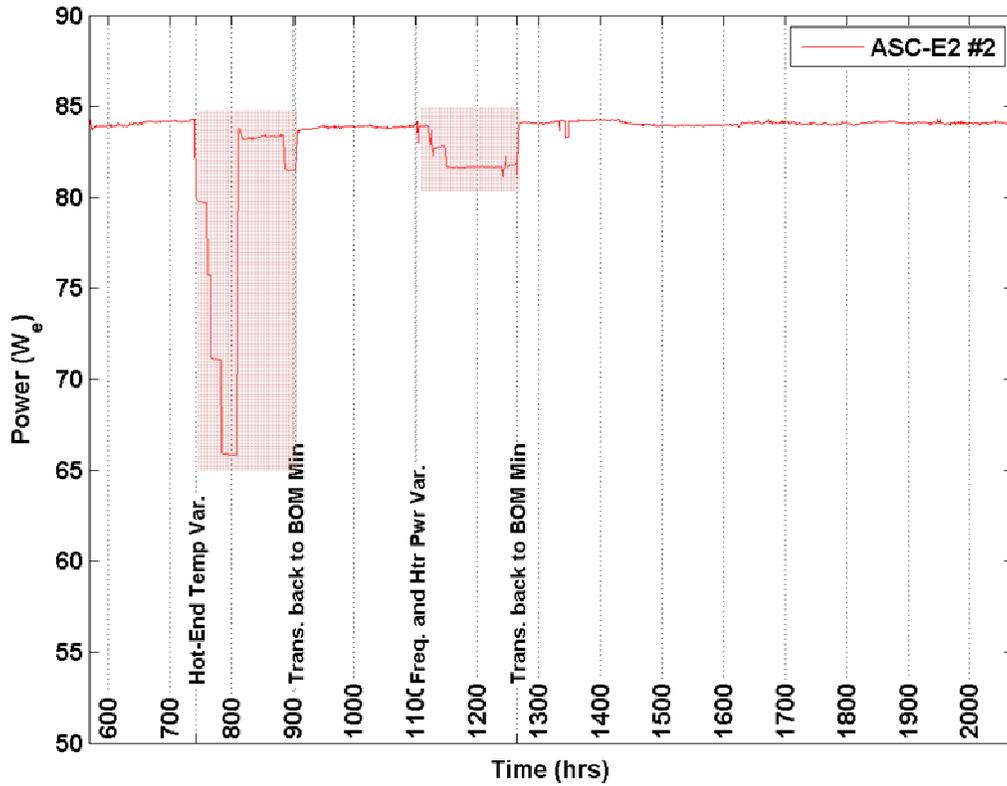


Figure 7. Power output performance data from ASC-E2 #2.

F. ASC-E2 #3 and #4

ASC-E2 #3 and #4 were delivered to GRC on April 28, 2010, and are being prepared for acceptance testing and extended operation. Insulation loss testing was completed to characterize the thermal losses from the insulation package. The converters will complete acceptance testing before being put into extended operation testing for 500 hr. They will be used for controller testing at LMSSC. Performance data is not shown for these converters due to the relatively low number of extended operation hours accumulated thus far. Figure 8 shows the converters in dual-opposed configuration in a vertical orientation. The converters are not actually visible in the figure because they are contained inside the insulation surrounding the alternator housing. The insulation was added to prevent thermal losses from thin-film heaters and a cooling loop located on the alternator housing. The heaters and cooling loop are needed to maintain alternator housing temperature during performance mapping. Table III summarizes ASC-E2 average performance data for extended operation.

Table III. Summary of ASC-E2 Extended Operation Data

Parameter	Units	ASC-E2 #2	ASC-E2 #3	ASC-E2 #4
		Single	Dual-opposed configuration	
Average hot-end temperature	°C	849.0	842.0	842.3
Rejection temperature	°C	52.0	49.1	50.1
Alternator housing temperature	°C	61.0	60.4	59.2
Gross heat Input	W _{th}	402	396	377
Gross efficiency	%	22.0	21.4	21.9
Alternator power output	W _e	88.0	84.9	82.6
Operating frequency	Hz	102.2	102.2	102.2

ASC-E2 #2 data averaged from 1300 to 2000 hr

ASC-E2 #3 and #4 data averaged over first 100 hr

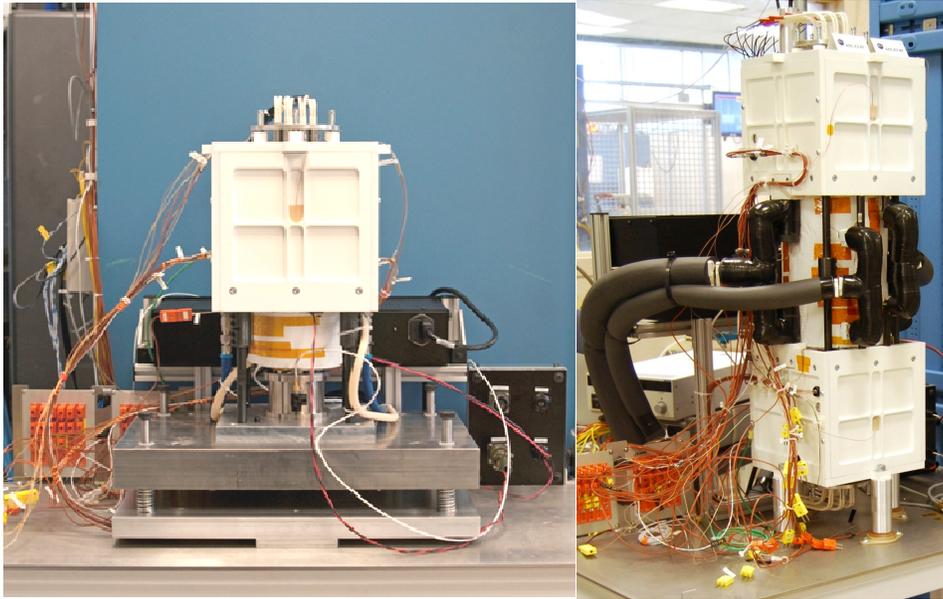


Figure 8. ASC-E2 #2 (left) and ASC-E2 #3 and #4 (right).

IV. Additional Ongoing Stirling Tests at GRC

In addition to ASC-E and ASC-E2 testing, other Stirling convertors are on extended operation testing at GRC. The Technology Demonstration Convertors (TDCs) #13 and #14 are the longest running pair of Stirling convertors at GRC, each with over 54,000 hr (6.1 years) of operation. TDC #15 and #16 have accumulated over 40,000 hr (4.5 years) of operation and ASC-0 #3 and #4 have accumulated over 18,600 hr (2.1 years) of operation under extended operation testing.

G. ASC-0 #3 and #4

The ASC-0 #3 and #4 units are the longest running pair of ASCs at GRC with over 18,600 hr (2.1 years) of operation. They began operation at GRC in August 2007 and were designed with Inconel 718 heater heads and hermetically sealed flange joints. Their nominal design conditions are 650 °C hot-end temperature, 90 °C rejection temperature, and 4.50 mm piston amplitude. Figure 9 shows power output and net efficiency to date for ASC-0 #3 and #4. Fluctuations in performance are attributed to shutdowns for instrumentation calibration and fill tube pinching.⁵ Extended operation testing continues today.

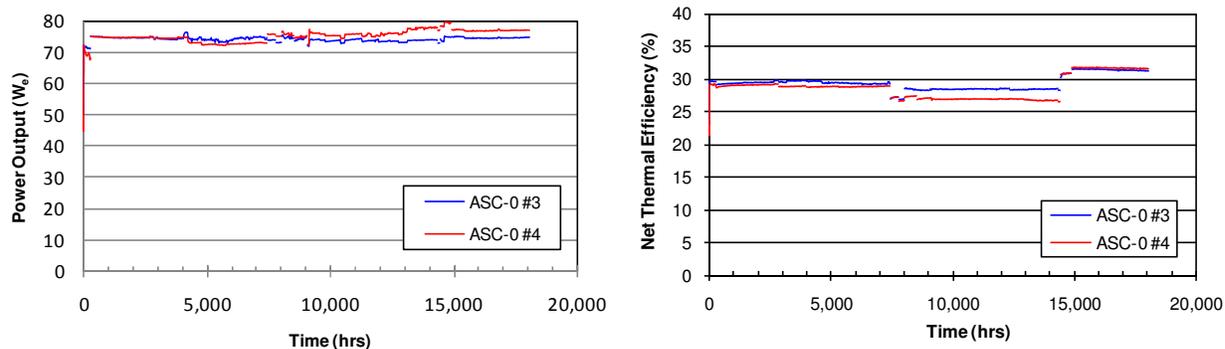


Figure 9. Power output and efficiency performance data from ASC-0 #3 and #4 through 18,600 hr of operation.

A. TDC #13 and #14

TDC #13 and #14 are the longest running pair of Stirling convertors at GRC, with over 54,000 hr (6.1 years) of operation. Extended operation of these convertors began in June 2003 and continues today. Figure 10 shows power output and net efficiency to date for TDC #13 and #14. Fluctuations in performance are attributed to regenerator oxidation caused by oxygen permeation through the o-ring seals, hermetically sealing the flanges intended to prevent further oxidation, low power testing before vacuum bakeout was performed, cartridge heater aging effects and failures, and drift in the Zener controller.⁵

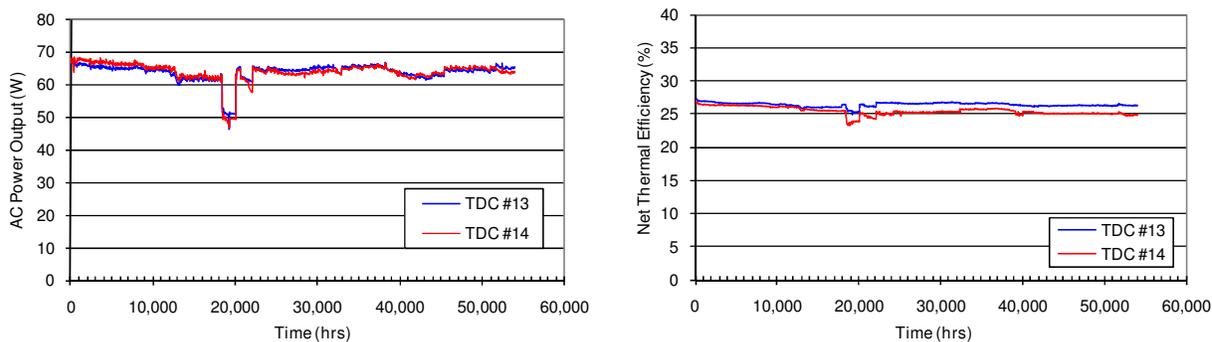


Figure 10. Power output and efficiency performance data from TDC #13 & #14 through 54,000 hr of operation.

B. TDC #15 and #16

TDC #15 and #16 are the second longest running pair of Stirling convertors at GRC, with over 40,000 hr (4.5 years) of operation. Extended operation of these convertors began in March 2005. Figure 11 shows power output and net efficiency to date for TDC #15 and #16. The fluctuations in performance are attributed to low temperature operation, hermetically sealing the flanges intended to prevent regenerator oxidation, low temperature operation before vacuum bakeout was performed, cartridge heater aging effects and failures, and drift in the Zener controller.⁵ As with TDC #13 and #14, the helium fill tubes remain connected to the gas management system to allow for analysis of the working gas throughout extended operation. Extended operation testing continues under the current test goals. TDCs #13 through #16 have continued to operate on extended operation testing as an integral part of GRC’s development of long-life RPSs. Table IV summarizes ASC-0 and TDC average performance data for extended operation.

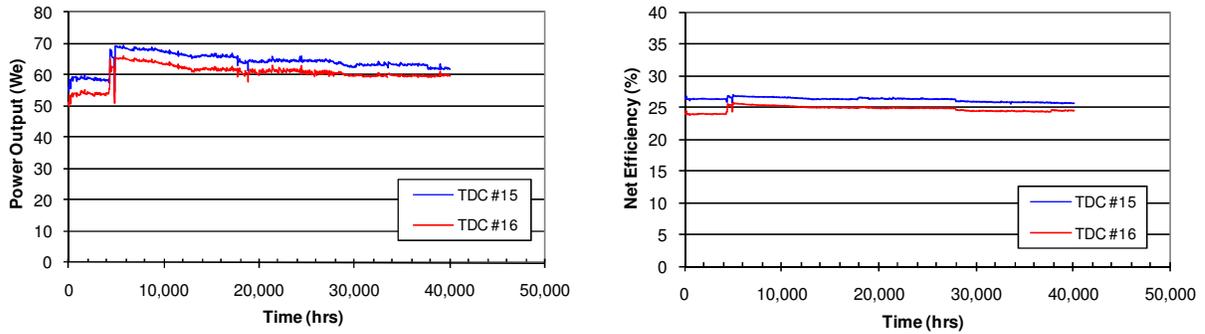


Figure 11. Power output and efficiency performance data from TDC #15 and #16 through 40,000 hr of operation.

Table IV. Summary of ASC-0 and TDC Extended Operation Data

Parameter	Units	ASC-0 #3	ASC-0 #4	TDC #13	TDC #14	TDC #15	TDC #16
		Dual-opposed config.		Dual-opposed config.		Dual-opposed config.	
Average hot-end temperature	°C	646.0	645.6	644.0	644.0	645.3	644.4
Rejection temperature	°C	91.0	91.6	78.9	81.2	80.4	80.8
Alternator housing temperature	°C	89.0	89.8	45.5	44.5	45.7	45.5
Gross heat input	W_{th}	327	338	279	288	281	281
Net heat input	W_{th}	239	243	248	256	247	250
Gross efficiency	%	22.8	22.8	23.3	22.1	21.9	21.2
Net efficiency	%	31.3	31.6	26.2	24.8	25.0	23.8
Alternator voltage	V_{rms}	22.9	22.9	86.2	86.1	84.1	84.3
Alternator current	A_{rms}	3.4	3.5	0.85	0.82	0.86	0.78
Alternator power output	W_e	74.6	76.9	65.1	63.6	61.8	59.6
Charge pressure (absolute)	MPa	n/a (hermetically sealed)		2.612	2.612	2.618	2.621
Piston amplitude	mm	4.49	4.41	5.48	5.22	6.06	5.98
Operating frequency	Hz	104.2	104.2	81.6	81.6	81.84	81.80

ASC-0 #3 and #4 data averaged from 17,000 to 18,000 hr

TDC #13 and #14 data averaged from 53,000 to 54,000 hr

TDC #15 and #16 data averaged from 39,000 to 40,000 hr

V. Conclusion

Stirling convertors have been operated for a total of more than 336,000 hr in Glenn Research Center's (GRC's) Stirling Research Laboratory. Test activities have enabled the refinement of convertor technology, test support hardware, and test controls and data collection systems. GRC provides direct technology support to the Department of Energy/Lockheed Martin Space Systems Company Advanced Stirling Radioisotope Generator (ASRG) flight project in the areas of reliability, convertor and generator testing, high-temperature materials, structures, modeling and analysis, organics, structural dynamics, electromagnetic interference (EMI), and permanent magnets to reduce risk and enhance reliability of the convertor as this technology transitions toward flight status. Convertor and generator testing is carried out in short- and long-duration tests designed to characterize convertor performance when subjected to environments intended to simulate launch and space conditions. Testing involves developing support hardware that enables 24/7 unattended operation and data collection. GRC currently has 14 Stirling convertors under unattended extended operation testing, including two operating in the ASRG Engineering Unit (ASRG-EU). As currently planned, all Advanced Stirling Convertor (ASC)-E2s will be in operation at GRC by the end of 2010. The subsequent phase of technology development, the ASC-E3 convertor, will be designed and tested with the focus on refining the manufacturing processes.

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