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Abstract

A high-efficiency radioisotope power system was being developed for long-duration NASA space science missions. The U.S. Department of Energy (DOE) managed a flight contract with Lockheed Martin Space Systems Company to build Advanced Stirling Radioisotope Generators (ASRGs), with support from NASA Glenn Research Center. DOE initiated termination of that contract in late 2013, primarily due to budget constraints. Sunpower, Inc., held two parallel contracts to produce Advanced Stirling Convertors (ASCs), one with Lockheed Martin to produce ASC–F flight units, and one with Glenn for the production of ASC–E3 engineering unit "pathfinders" that are built to the flight design. In support of those contracts, Glenn provided testing, materials expertise, Government-furnished equipment, inspection capabilities, and related data products to Lockheed Martin and Sunpower. The technical support included material evaluations, component tests, convertor characterization, and technology transfer. Material evaluations and component tests were performed on various ASC components in order to assess potential life-limiting mechanisms and provide data for reliability models. Convertor level tests were conducted to characterize performance under operating conditions that are representative of various mission conditions. Despite termination of the ASRG flight development contract, NASA continues to recognize the importance of high-efficiency ASC power conversion for Radioisotope Power Systems (RPS) and continues investment in the technology, including the continuation of the ASC–E3 contract. This paper describes key Government support for the ASRG project and future tests to be used to provide data for ongoing reliability assessments.

Nomenclature

ACU	Advanced Stirling Convertor Controller Unit
ASC	Advanced Stirling Convertor
ASC–E	Advanced Stirling Convertor Engineering design #1
ASC–E2	Advanced Stirling Convertor Engineering design #2
ASC–E3	Advanced Stirling Convertor Engineering design #3
ASC–F	Advanced Stirling Convertor Fight design
ASRG	Advanced Stirling Radioisotope Generator
CPH	Common Performance Hardware
CT	computed tomography
DOE	Department of Energy
FEA	finite element analysis
FLDT	Fast Linear Displacement Transducer
GCF	gigacycle fatigue
GHA	Generator Housing Assembly
MTTF	mean time to failure
NDI	nondestructive inspection

RGA	residual gas analyzer
RPS	Radioisotope Power Systems
SRG–110	Stirling Radioisotope Generator 110 W

Introduction

The Advanced Stirling Radioisotope Generator (ASRG) was being developed for long-duration space science missions by the U.S. Department of Energy (DOE) and Lockheed Martin Space Systems Company. In late 2013, the ASRG flight contract began termination largely due to budget restrictions. Prior to termination, the majority of tasks related to assessing reliability were completed with only long-term tasks continuing, including materials aging tests and convertor extended operation. Such support included performing thermal, structural, and dynamic analysis, providing materials expertise, equipment, and unique inspection capabilities, and performing reliability tests on components, convertors, and generator systems. Glenn started extended Stirling convertor tests in 1999 and has since conducted operational evaluations in support of the Stirling Radioisotope Generator 110 W (SRG–110) and ASRG projects. For the ASRG project, convertor production consisted of two parallel contracts with Sunpower, Inc., one managed by Lockheed Martin to produce the ASC–F flight units and the other managed by Glenn to produce ASC–E3 engineering units that served as pathfinders by being built to the flight specification and documentation. The first four ASC–E3s were delivered by Sunpower to Glenn between November 2012 and August 2013.

Accelerated life tests were performed for Advanced Stirling Convertor (ASC) components, including the heater head, planar spring, fasteners, various organic materials, and power feedthrough. Convertor testing characterizes the response to external random vibration, overstress conditions intended to operate in the design margins in order to stress the convertor without failure, and nominal conditions intended to evaluate performance over long durations. Nondestructive inspection (NDI) of the heater head assembly, a critical component of the ASC, has been performed to provide a unique in-process inspection capability. Analysis results have been provided as inputs for verification of certain ASC specification requirements.

The ASC–E3 started production with the goal being built to the same design and processing documentation and the same flight ASC product specification. The first two pairs of ASC–E3s were planned to be process pathfinders, followed by two pairs of "flight-like" convertors. The first two pairs of ASC–E3s were used to reduce risk and validate design and processing changes prior to implementation on the ASC–F convertors. The last two pairs of ASC–E3s were being built using the flight-approved documents and are representative of the flight convertors. The third pair of convertors, shown in Figure 1, should be delivered this fall and the last pair by early next year (Ref. 1).

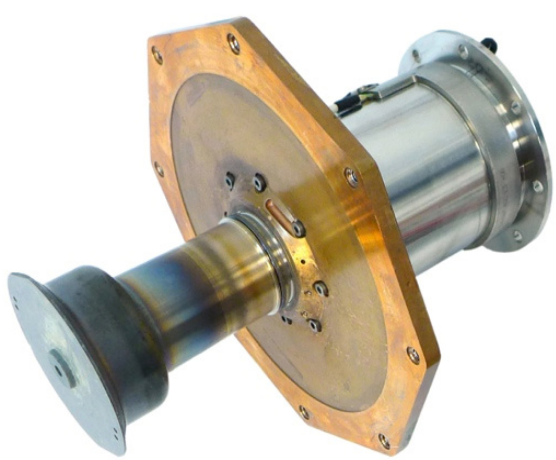

Figure 1.—Completed ASC–E3 #5.

Glenn's technical support activities focus on lowering risk and addressing reliability for the long-life application. Establishing life and reliability of Stirling convertors of this general type, based on noncontacting operation and the elimination of wear mechanisms by design, prove challenging. While components can be tested at accelerated conditions, the entire operating Stirling convertor cannot. The ASRG reliability effort had been formulated to be multifaceted, because the statistical test durations to meet life requirements are more than the 17-year ASC life requirement. It makes use of classic techniques such as failure modes, effects, and criticality analysis; reliability block diagrams; and fault tree analyses. It also includes probabilistic techniques that are applied to many of the key components such as the heater head. Extended operation of convertors provides further data regarding any potential aging effects. The approach follows a sequence of (1) identifying risks and potential failure modes, (2) characterizing the potential failure modes, (3) mitigating the risks associated with each failure mode to an acceptable level, and (4) accepting those risks after mitigation steps are complete (Refs. 2 and 3).

Material and Component Evaluation

Material evaluations have been performed on various components in the ASC in order to predict potential life-limiting mechanisms or provide reliability models with more accurate input data. The heater head assembly is one such key component in the ASC. This thin-walled component has had numerous evaluations and analyses performed, including uniaxial creep testing of thick and thin specimens of the high-temperature superalloy 247-LC. Glenn materials and structures personnel have developed an approach to characterize the long-term durability of the heater head, including both deterministic and probabilistic methods. Other evaluations performed include gigacycle tests of the material used for the displacer planar spring, ductility testing of the fasteners, and evaluation of the multiple organic materials used in the cold end of the convertor. Organics accelerated testing characterized material limits or functionality based on moderately higher temperatures over time in different environments. In situ outgassing assessment under gamma radiation, compatibility of off-gassed organics, thermal stability, and mechanical integrity of epoxies were performed. Some of the ASC component activities are shown in Figure 2.

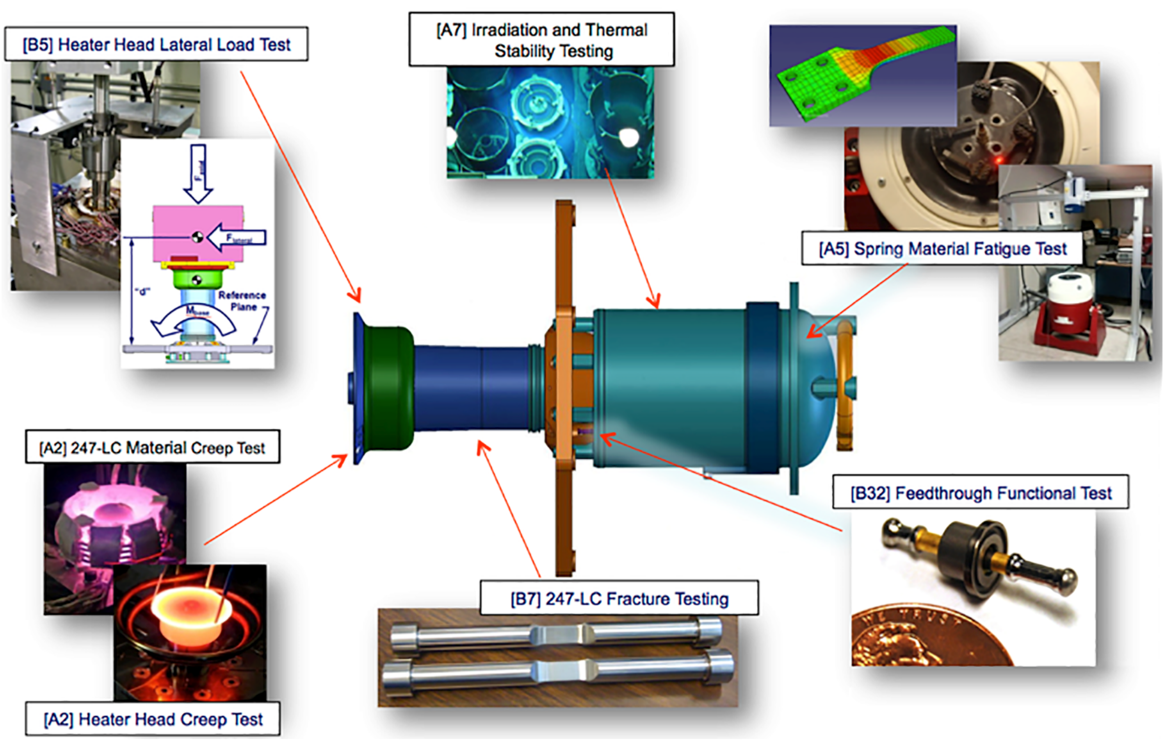

Figure 2.—ASC with accelerated component testing performed for the ASRG project.

Heater Head

A significant focus of Glenn structural analysis has been on the heater head, due to the limited availability of 247-LC material properties. In order to enable a heater head design with a high probability of meeting the requirement of the 17-year design life, Glenn structural engineers developed guidelines and performed characterization tests on material coupons, intermediate machined components, and final machined subassemblies. The test and analysis campaign resulted in positive margins for through-thickness average creep strain, limits for local creep strain, and the time at the onset of tertiary creep (Refs. 2 and 3). The various successful heater head tests performed included

1. Benchmark creep tests of fully machined heater heads to verify long-term creep behavior at 1.4 times the peak pressure and a localized head temperature of 861 °C (above the current 760 °C operating temperature)
2. Lateral load testing of a complete heater head assembly to simulate high loading conditions at axial and lateral load conditions
3. Material characterization to verify fracture toughness, fracture crack growth rate, and fracture threshold
4. Permeation testing to verify no leakage through thin wall specimens at 850 °C with up to 6 percent strain of the material (significantly above anticipated lifetime creep)

Secondary Locking Mechanism

A test program was developed to evaluate the fastener locking mechanisms for the ASC threaded fastener joints and various Loctite liquid locking compounds. The requirements were based on the NASA specifications, NASA–STD–5017, “Design and Development Requirements for Mechanisms,” and NASA–STD–5020, “Requirements for Threaded Fastening Systems in Spaceflight Hardware,” and the final report from NASA Engineering and Safety Center (NESC) investigations, NESC–RP–04–092, “Performance Characterization of Loctite® 242 and 271 Liquid Locking Compounds (LLCs) as a Secondary Locking Feature for International Space Station (ISS) Fasteners.” The test effort consisted of three phases, including the determination of baseline control properties, evaluation of installation variables and processes, and evaluation of cure kinetics and thermal stability. Procedures and test conditions were developed to identify processing sensitivities of the liquid locking compounds, factoring in test specimen fabrication, environmental thermal aging, torque strength, and other thermal and structural parameters. The test matrix was evaluated in terms of cure state, thermal stability, and fastener locking integrity. The designs of torque test specimens followed the actual fastener joint configurations as close as possible. In order to evaluate torque, a high-resolution torque testing system was developed and certified at NASA Glenn. The effort successfully tested 720 torque test specimens at various temperatures, up to 150 °C for the ASC fastener joints. The results demonstrated positive margins in the ASC fastener joint designs.

Gigacycle Spring Material

The planar spring, attached to the displacer, undergoes roughly 55 billion stress cycles during the 17-year design life. Previously, overstressed accelerated life testing on fully processed displacer planar springs were completed with no failures. To further verify fatigue endurance of the spring material, Glenn experts directed a high-cycle accelerated fatigue test effort at the University of Akron, Akron, Ohio. The gigacycle fatigue (GCF) test methodology was designed to subject cantilever beam specimens processed similarly to displacer planar springs in a high-frequency resonant mode. The effort successfully designed and manufactured stable specimen fixtures, established test procedures, and developed system safety interlocks and monitoring for long-term tests using the electrodynamic shaker. The effort successfully characterized the number of stress cycles endured by the specimens over a stress range of 540 to 850 MPa.

The results showed that fatigue cracks initiated and propagated at stress levels of 775 MPa and above, while tests below this level were runouts, with no fatigue cracks evident up to 20 billion cycles. The high-cycle fatigue testing further demonstrated the reliability of the displacer planar spring materials.

Synergistic Durability Aging Tests on Organics

The combined effects of irradiation, thermal exposure, and synergistic organic outgassing interactions on stability and durability of ASC organics were assessed with a simulated thermal aging test. This test involved all ASC organic materials, which were preconditioned with various irradiation exposure conditions under either gamma or reactor neutron radiation from the previous NASA Glenn tasks in order to simulate irradiation from the radioisotope heat source and potential mission environments. Aging temperature was determined to be 130 °C based on the maximum alternator qualification temperature. The test vessels holding organic samples in either coupon or actual part configurations were pressurized and sealed with the ultra-high-purity helium to create a representative ASC internal gas environment. Short- and longer-term aging tests were initiated simultaneously. After these synergistic durability aging exposures, the resulting gas including generated outgas species from the organics were carefully analyzed. Additionally, systematic residual property characterizations were performed on the material specimens to determine potential changes by comparing directly with those of various unaged control specimens. The results were also compared with the property changes from the isolated thermal aging tests of individual organics at the similar temperature range but under a controlled inert gas environment in order to further ascertain the effects of the synergistic durability aging. The 5- and 16-month aging tests results suggest that ASC organics will continue to function reliably for the intended life.

Power Feedthrough Thermal Exposures

The ASC flight design has two power feedthroughs and reliability of this component is essential. Tests were designed to subject power feedthrough test samples to thermal cycling, long-term aging, hermeticity testing, and structural tests. These tests were aimed at demonstrating functionality after a series of increased peak temperatures. For thermal cycling, the samples experienced 150 cycles at five temperatures up to a peak test temperature of 250 °C, twice the maximum operating temperature. Some of those samples were subjected to structural testing aimed at providing finite element analysis (FEA) models with more realistic strength properties for the pin to sealer joint present in the feedthrough. Additional tests subjected flight feedthroughs to low-temperature thermal cycling test, consisting of 150 thermal cycles, ranging from 0 to 125 °C, and then long-term aging at 125 °C. This test was designed to demonstrate functionality after exposure to simulated minimum and maximum qualification conditions. All samples passed the ASC specified hermeticity requirement and demonstrated functionality after exposure to two times the maximum application temperature and 150 thermal cycles for the extreme qualification conditions.

ASC Testing

Convertor testing enables characterization of ASC performance using operating conditions representative of various reference phases of a mission. These phases include production, receipt, integration, launch, and cruise. Convertors can accumulate several thousand hours before entering the extended operation. Once in simulated cruise, they are operated unattended by test personnel for several years. During that extended period of operation, convertor operation is interrupted for annual facilities maintenance and to perform periodic checkout tests, which are used to show convertor performance has not degraded over time. Also, overstress conditions verify that the convertor can survive operation in select severe conditions and perform as expected after returning to nominal conditions. Some tests are operated in the vertical orientation while others are performed horizontally. Figure 3 shows convertors in single-vertical orientation and in dual-opposed horizontal, where the dynamic disturbances of operating convertors are canceled out. Both types of tests continue to provide input data for the life certification plan (Ref. 4). Operating hours for multiple convertors are accumulated and used to calculate the mean time to failure (MTTF) for random failures.

Testing of Stirling convertors in the Glenn Stirling Research Laboratory was initiated in 1999 at Glenn and has accumulated over 660,000 hr. Of these, 316,000 hr are associated with varying generations of the Sunpower ASC engineering units. Table I shows only relevant convertors that are still in operation, as well as future ASC–E3s, which are scheduled for delivery in 2014 and 2015.

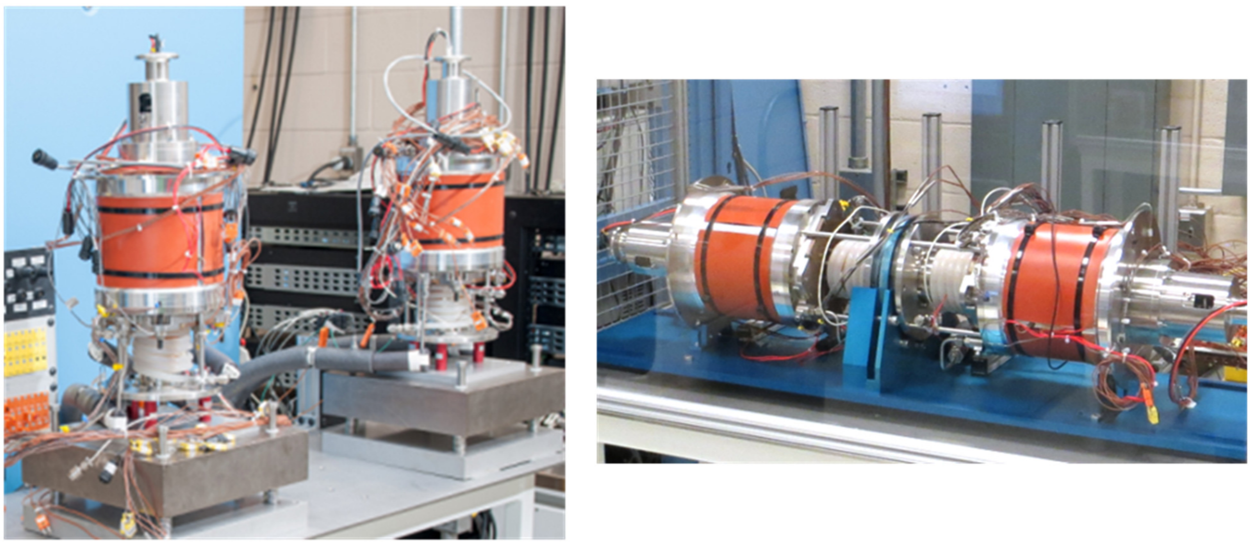

Figure 3.—ASC–E3 test configurations. Single vertical (left) and dual-opposed horizontal (right).

TABLE I.—ASC TEST STATUS AS OF JULY 7, 2014

ASC	Location	Current use	Control	Test setup[a]		Next phase	Hours
E3 #1	Glenn	Demonstration	AC Bus and ACU	Dual-opposed, vertical	Flight-like GHA	ACU	3109
E3 #2	Glenn					ACU	3104
E3 #3	Glenn	Extended operation	AC Bus	Single-vertical	CPH	Dual-opposed, horizontal	3970
E3 #4	Glenn	Extended operation	AC Bus	Single-vertical	CPH		4939
E3 #5	Sunpower	Future deliveries	AC Bus	Single-vertical planned during acceptance testing	Delivered in CPH	Delivery in fall 2014	
E3 #6							
E3 #7						Delivery in spring 2015	
E3 #8							
E2 #4	Glenn	Extended operation	AC Bus	Dual-opposed, vertical	E2 support hardware	Dual-opposed, vertical	13,568
E2 #5	Glenn						27,316
E #2	Glenn	Extended operation	AC Bus	Dual-opposed, vertical	E support hardware	Dual-opposed, vertical	35,316
E #4	Glenn						31,248
0 #3	Glenn	Extended operation	AC Bus	Single-vertical	0 support hardware	Single-vertical	44,939

[a]Common Performance Hardware (CPH).

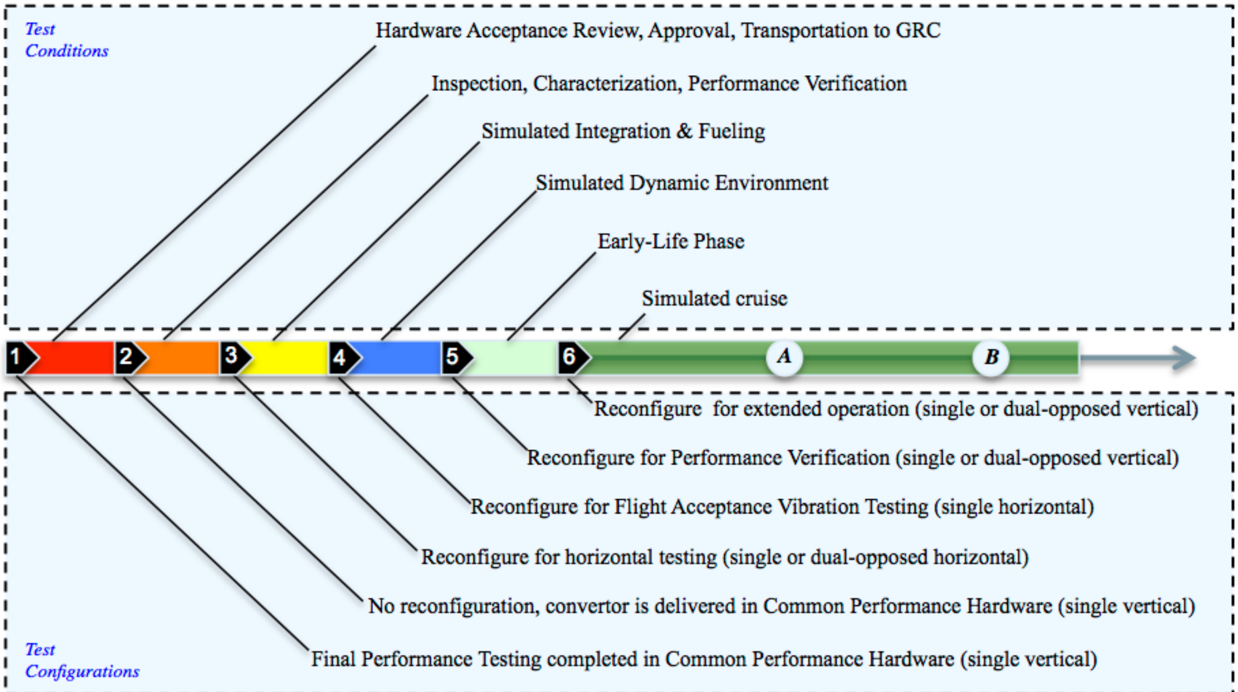

Figure 4.—ASC–E3 test sequence. Tests A and B are examples of continuing periodic checkout tests used to verify performance over time.

The ASC–E3 test sequence, summarized in Figure 4, enables independent performance verification, simulates relevant environments during the life cycle of a flight convertor within certain limits, and mitigates risk by providing the life certification plan with input data from nominal and overstress conditions. To start, each completed ASC convertor undergoes final performance testing at Sunpower before entering the hardware acceptance review. After approval, the convertors are delivered to Glenn for additional testing. In sequence 2, the ASC undergoes receipt inspection, characterization, and performance verification. In an effort to minimize variation between the two locations and thus minimize differences in the test data, the convertors are delivered in the same test setup used to verify performance at Sunpower, called the Common Performance Hardware (CPH). The tests also utilize similarly designed data acquisition systems and control racks to minimize variations in test results that are unrelated to convertor performance. Once approved, the test sequence will provide guidance for tests that provide data for life certification.

The specified operating points were designed to simulate reference mission conditions, such as at the beginning and end of a mission, when the amount of available heat varies due to the natural decay of the radioisotope heat source. Different test conditions and configurations simulate various relevant environments throughout the life of a flight convertor. Horizontal operation simulates ground integration and fueling, random vibration testing simulates launch conditions, and extended operation is used to simulate a cruise phase. During the simulated cruise phase, periodic checkout tests are performed to monitor for any performance changes. Checkout tests include a natural frequency test to ensure the spring stiffness or gas spring stiffness have not changed and performance tests to ensure conversion efficiency has not changed.

In February 2014, ASC–E3 #4 was exposed to external random vibration in the X-, Y-, and Z-axes, while operating at slightly less than full power. Flight acceptance and launch simulation vibration levels were performed for 1 min each test, resulting in a total of 2 min exposure in each axis. After vibration tests, the convertor was returned to extended operation in a single-vertical orientation and is now being prepared for test sequence 3, where it will undergo horizontal testing.

Overstress Testing

Durability tests are intended to stress convertors by operating outside limits imposed by the ASC specification and experimentally demonstrate the existing margins in the design. After the overstress testing has been completed, the convertors are intended to transition into extended operation. These tests subject a convertor to the possibility of lateral contact between the moving components and running surfaces and/or axial contact of the moving components to hard limits. Four durability tests were originally planned, including (1) repeated starting and stopping of the convertor to simulate ground processing prior to fueling, (2) exposure to constant acceleration to simulate liftoff or landing, (3) exposure to random vibration testing at higher piston amplitudes, inciting a number of piston and/or displacer contact events to simulate worst-case launch conditions, and (4) temporarily disabled control to simulate off-nominal card switcher events, allowing contact events over a controlled duration. The first two tests have been completed and the last two may be replanned due to project priorities.

Start/Stop Testing

In September 2011, ASC–E2 #8 was used by Glenn and Sunpower personnel to complete a total of 300 start/stop cycles, simulating startup and shutdown over the lifetime of a typical flight unit, with an over-test factor of two times. The convertor was motored in horizontal and vertical orientations and in a range of cold-end temperatures expected of the ASC, including 200 in the vertical orientation and 100 cycles in the horizontal orientation. During startup and shutdown, the self-pressurizing gas bearings are activated and deactivated, allowing brief contact between the running surfaces. This test was used to characterize any potential degradation on the internal convertor surfaces due to starting and stopping. Post-test disassembly and inspection, as well as gas bearing flow tests, indicated no evidence of wear or gas bearing degradation (Ref. 5).

Constant Acceleration

In May 2012, Glenn completed the constant acceleration tests using ASC–E2 #2 at Case Western Reserve University's centrifuge facility (Ref. 5). To prepare for the test, convertor rework included installing a removable pressure vessel to enable interim inspections of the internal running surfaces and installation of more accurate piston and displacer Fast Linear Displacement Transducer (FLDT) position sensors. The test was envisioned to simulate the static acceleration force anticipated during launch from a boost thruster or from reentry and landing. However, the spin-up time of the centrifuge facility took significantly longer than the specified flight durations, resulting in an over-test condition for exposure time to elevated levels of acceleration. To simulate various mounting orientations, testing was carried out with a constant acceleration force imparted in the axial direction toward the heater head, in the axial direction away from the heater head, and in the lateral direction, the latter of which is expected to be the most challenging orientation. Test objectives included characterization of convertor performance when exposed to 18 g constant acceleration profile and evaluation of the effects on the convertor Xylan (Whitford) surfaces when the forces from lateral acceleration exceed the gas bearing load capacity. The axial tests were performed before the lateral tests at an acceleration of 18 g. The acceleration was increased for lateral tests: 8, 12, and 18 g were applied between inspection of the running surfaces. After testing was completed, review of the performance data showed differences within the margin of measurement error and inconsequential minor "polishing" of the surfaces was noted confirming that lateral contact did occur as expected but did not result in degradation of the Xylan surfaces.

ASC Piston Contacts During Random Vibration

Random vibration tests are used to expose test articles to the harsh environment of launch. As vibration levels increase, the mean position of the moving components vary randomly and the piston amplitude can increase for a limited number of cycles before returning to the nominal mean position and amplitude. These excursions could result in piston and/or displacer contact events. Testing had already started on this effort and was broken into three parts. Most of the characterization testing and inspections had been completed prior to ASRG termination. Future plans could include finishing this test.

ASC Piston Contacts During Out-of-Control Event

An out-of-control event is a duration where control of the convertor is temporarily disabled and could allow a limited number of contact events. Earlier analysis results suggest such an event could happen during controller card switchover (Ref. 3). Demonstrations of the Lockheed Martin controller switchover functionality indicates proper performance without loss of control. Analysis was also used to determine the velocities at which permanent component deformation would occur, in order to establish test limits to avoid damage to the convertor and enable extended operation. Plans were under development to simulate this condition and enable quantification of contact events, but they were put on hold after ASRG termination.

Thermal Cycling

Overstress testing can also be achieved by thermal cycling particular components to simulate conditions anticipated in application. Lockheed Martin recommended the next two test aspects and had adopted them into the ASRG life test approach. To learn about temperature effects on performance, the cold-end temperatures would be cycled between end-of-mission low reject and a high reject point to simulate extreme environments on alternator components. Plans are being evaluated for implementing a version of these overstress conditions into ongoing ASC–E3 performance tests. It is important to point out that these operating conditions do not exceed conditions experienced during Sunpower production tests.

Increased Piston Amplitude

Running at slightly higher piston amplitude provides additional means of overstress and was also adopted into the Lockheed Martin's ASRG life test approach. This accelerates any wear on moving parts and could be implemented into extended operation. Similar to thermal cycling, plans are also being evaluated for potential implementation, however, a limit has not been selected. A likely candidate would be higher amplitudes experienced during production testing.

Government-Provided Inspection, Analysis, and Equipment

Glenn provided a variety of unique capabilities from 2010 to 2012, including performing in-process inspection of flight heater heads, providing convertor performance predictions, and providing test support personnel, equipment, and convertors to enable key tests. The in-process inspection was performed as a screening technique on all ASC–E3 and ASC–F heater heads to ensure they passed hermeticity requirements prior to installation on a convertor. There is the possibility of casting defects to allow the working gas to leak through at rates that exceed specified requirements (Ref. 6), because the heater heads are fabricated from cast material. Such leakage would decrease the charge pressure and degrade performance over the life of the mission. The first inspection technique used Glenn's x-ray Microfocus Computed Tomography (CT) system, able to identify casting imperfections in the thin wall and taper region of the superalloy cylinder of the heater head. The second method is the high-temperature leak test, designed to detect helium leaks caused by through-thickness defects that were too thin for detection using Microfocus CT x-ray. When the NDI effort was completed in May 2013, a total of 34 heater head assemblies had been processed at Glenn. These efforts were completed to ensure that the heater heads selected for use on flight were of the utmost quality, able to maintain hermeticity, and meet the thermal and structural requirements of the ASC.

Microfocus CT X-ray

The Glenn Microfocus CT system is considered to be one of the best in the United States and is ideally suited for this application (Ref. 7). Able to detect defects as small as 11 µm, the state-of-the-art capability is able to screen out any defects that are larger than the crucial flaw size of the head. Microfocus CT creates a three-dimensional model of the inspected object by computer processing and reconstructing a very large series of high-resolution two-dimensional x-ray images taken of the object around a single axis of rotation. To determine accuracy, a probability of detection study was conducted using a precisely machined calibration standard made from an actual ASC thin-walled heater head containing an array of target features with varying width and depth.

High-Temperature Helium Leak Testing

The Glenn setup, shown in Figure 5, was originally developed to verify that the convertor's helium working gas would not permeate through the walls at representative pressures and temperatures. The test setup consists of a vacuum chamber used to create the high vacuum environment, which avoids oxidation during the test and allows the use of a residual gas analyzer (RGA) to detect leaking helium. It contains a tantalum heating element to impart the 850 °C maximum hot-end temperature (nominal ASRG hot-end temperature is 760 °C) and a mounting flange, which cools the other end of the heater head to around 200 °C. To enable a seal that is also able to meet the required leak rate, a very tight crushed metallic seal

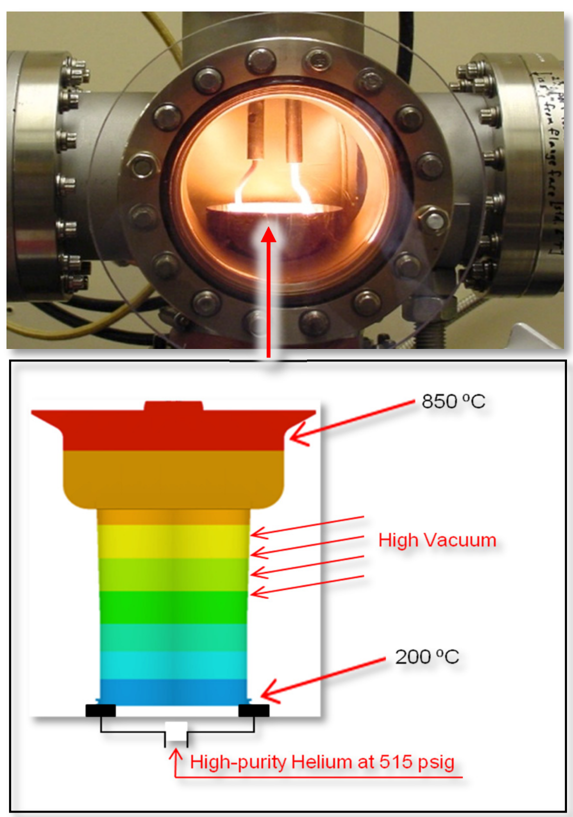

Figure 5.—High-Temperature Leak Test Facility.

was used between the heater head assembly open end and the actively cooled mounting flange. Therefore, this test setup simultaneous detected any helium leakage through the heater head wall and through the crushed metallic seal. An RGA was used to compare the response from the tested heater head and from a calibrated leak standard. This resulted in a simple approach to verifying the hermeticity requirement for each heater head prior to production use.

Test Support Equipment

To support ongoing ASC–E3 production, ground support equipment was provided to Sunpower to enable autonomous continuous operation of convertors. Such test methods were developed at Glenn to enable routine continuous safe operation of the convertors. Rack components, including the Failsafe Protection Circuits and ASC piston sensor Buffer Circuit, prevent higher-than-desired piston amplitudes during facility malfunctions during unattended continuous operation. They enable safe autonomous shutdown while test personnel are not present. Also, long-life electric heat sources are being provided to enable longer duration testing without the need for more frequent teardown of the test setup. This minimizes disruptions in the Sunpower production schedule and post-delivery Glenn testing and further reduces handling of the delicate microporous insulation.

High-Fidelity Computation

In an effort to improve accuracy of performance predictions, a high-fidelity computational model was developed at Glenn to predict convertor net heat input, a key parameter needed to determine thermal-to-electric conversion efficiency. Performance predictions were calculated for the earlier ASC–E2s and provided to Lockheed Martin to support the ASRG Preliminary Design Review in December 2010 and again in 2012 to support the Final Design Review. Performance predictions were calculated for ASC–E3s and provided to Sunpower to aid in performance verification and for inclusion in the end item data packages for the first two pairs of delivered convertors. Plans are currently underway to complete the same calculations on the third pair of ASC–E3s, followed by an analysis to determine how close this high-fidelity computational method is to a lower fidelity method used at Sunpower. So far, the two methods have been close so it is anticipated that the high-fidelity results, which are more time consuming and expensive may be phased out for future ASC–E3 convertors tested in the CPH (Ref. 8).

Convertors Provided for Controller Tests

Glenn provided Government-owned convertors and test support for ongoing controller characterization from 2010 to 2014. Such testing enabled Lockheed Martin to characterize various generations of the ASC Controller Unit (ACU), using the highest fidelity convertors as they became available. In August 2010, ASC–E2 Pair 2 was delivered to Lockheed Martin, mounted in a dual-opposed horizontal configuration. In March 2012, ASC–E2 Pair 4 was delivered in the single-vertical arrangement. In both of those cases, test support was provided to get the convertors integrated and operating for the first time using approved procedures. Lastly, ASC–E3 Pair 1 was provided in a dual-opposed horizontal configuration in September 2013 to enable successful demonstration of the highest fidelity ACU at that time, including system startup, ASC control and operation at nominal and worst-case operating conditions, power rectification, direct-current output power management, ACU fault management, and system command/telemetry (Ref. 9).

Controller support was also provided for random vibration testing on two occasions. First, ASC–E #1 was subjected to launch simulation vibration levels while being controlled by an early ACU (EDU 1) in February 2009. More recently, ASC–E2 #2 and ASC–E2 #8 were controlled by a later higher fidelity ACU (EDU 3) during qualification-level vibration tests in July and December of 2012, successfully demonstrating convertor control during random vibration of the ASC.

Conclusion

NASA Glenn Research Center provided materials, equipment, testing and inspection services, and related data products to Lockheed Martin Space Systems Company and Sunpower, Inc., in support of two parallel contracts to deliver engineering and flight Advanced Stirling Convertors (ASCs). These technical support tasks include material evaluations, component tests, convertor characterization, and technology transfer. Material evaluations and component tests have been performed on various components in the ASC in order to predict potential life-limiting mechanisms and provide inputs to reliability models. Convertor level tests were used to characterize performance at reference mission operating conditions. These accomplishments are not only relevant to continued interest in 80-W ASC but also apply to future, potentially higher power ASC, which will utilize much of the same technology. Despite termination of the Advanced Stirling Radioisotope Generator (ASRG) flight development contract, NASA continues to recognize the importance of high-efficiency ASC power conversion for Radioisotope Power Systems (RPS) and continues investment in the technology, including the continuation of the ASC–E3 contract. The first four ASC–E3s were delivered by Sunpower to Glenn and they continue to be used for a variety of tests to advance the state of the technology. The last two pairs of flight-like ASC–E3 convertors are planned for delivery late in 2014 and early 2015.

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