

NASA/TM—2015-218461

AIAA—2014—3962



Advanced Stirling Converter Development for NASA Radioisotope Power Systems

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Prepared for the
50th Joint Propulsion Conference
cosponsored by the AIAA, ASME, SAE, and ASEE
Cleveland, Ohio, July 28–30, 2014

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Acknowledgments

The work described in this paper was performed for the Science Mission Directorate (SMD) and the Radioisotope Power Systems (RPS) Program. The authors thank the ASC and ASRG integrated team for the many significant contributions to advancing Stirling RPS technology.

Level of Review: This material has been technically reviewed by technical management.

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Abstract

Sunpower Inc.'s Advanced Stirling Convertor (ASC) initiated development under contract to the NASA Glenn Research Center and after a series of successful demonstrations, the ASC began transitioning from a technology development project to a flight development project. The ASC has very high power conversion efficiency making it attractive for future Radioisotope Power Systems (RPS) in order to make best use of the low plutonium-238 fuel inventory in the United States. In recent years, the ASC became part of the NASA and Department of Energy (DOE) Advanced Stirling Radioisotope Generator (ASRG) Integrated Project. Sunpower held two parallel contracts to produce ASCs, one with the DOE and Lockheed Martin to produce the ASC-F flight convertors, and one with NASA Glenn for the production of ASC-E3 engineering units, the initial units of which served as production pathfinders. The integrated ASC technical team successfully overcame various technical challenges that led to the completion and delivery of the first two pairs of flightlike ASC-E3 by 2013. However, in late fall 2013, the DOE initiated termination of the Lockheed Martin ASRG flight development contract driven primarily by budget constraints. NASA continues to recognize the importance of high-efficiency ASC power conversion for RPS and continues investment in the technology including the continuation of ASC-E3 production at Sunpower and the assembly of the ASRG Engineering Unit #2. This paper provides a summary of ASC technical accomplishments, overview of tests at Glenn, plans for continued ASC production at Sunpower, and status of Stirling technology development.

Introduction

The 80-W-class Advanced Stirling Convertor (ASC) development was initiated by Sunpower, Inc., of Athens, OH, under contract to NASA Glenn Research Center with the goal of achieving breakthrough efficiency, a key objective of the NASA Radioisotope Power Conversion Technology (RPCT) Project (Ref. 1) through which the contract was funded. The goal of RPCT was to develop next-generation power conversion technologies that would provide improved performance over the systems that were being developed in the early 2000s, specifically the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and the Stirling Radioisotope Generator (SRG-110). The Sunpower ASC contract was 1 of 10 technology contracts awarded in 2003 that included a variety of conversion technologies and technology readiness levels that had the potential to enable RPS with high efficiency and low mass. The ASC technology provides high thermal-to-electric conversion efficiency reducing fuel requirements by a factor of four compared to thermoelectric systems, lowering system mass and enabling more nonsolar NASA Science missions given the small plutonium-238 fuel inventory in the United States.

The ASC is a free-piston Stirling engine integrated with a linear alternator that utilizes technologies from Sunpower’s cryocoolers, Sunpower’s 35-W convertor developed under a NASA Small Business Innovative Research (SBIR) contract, along with advancements developed for the ASC that provided breakthrough performance. The technologies included hydrostatic gas bearings to allow noncontacting operation of the moving components, moving magnet alternator, high-temperature heater head assembly utilizing nickel-based super alloy, oxidation-resistant high-porosity regenerator, displacer planar spring, piston centering system, and very small clearances for the piston and displacer. The strategy to develop the ASC under the NASA contract included multiple builds, each of which addressed objectives to evolve the technology in preparation for eventual flight production. Each successive build includes design and processing changes to meet newly defined requirements, improve manufacturability, or enhance reliability. The ASC-1 demonstrated 38 percent efficiency (88 W_{AC} power output, 850 °C T_{hot}, and 90 °C T_{cold}) (Ref. 2). Early technology demonstrators (ASC-1, ASC-0, and ASC-1HS) continued to demonstrate high efficiency, small size, and low mass of the basic ASC design and allowed for the development of weld joints needed for hermetic sealing of the convertors. The early successful demonstrations provided clear indications of the advantages of the ASC over other technologies being developed under the RPCT Project and also convinced decisionmakers at NASA and Department of Energy (DOE) that the ASC should transition from technology development to flight development.

The next phase of ASC development necessary prior to flight adoption was the development of the ASC engineering units. In 2006, the decision was made to adopt the ASC technology as part of the DOE and Lockheed Martin Advanced Stirling Radioisotope Generator (ASRG). Shown in Figure 1, the ASRG utilizes a pair of ASCs, each integrated with a General Purpose Heat Source (GPHS). In contrast to the earlier technology demonstration convertors that were designed for stand-alone laboratory operation, the ASC engineering unit ASC-E was developed specifically to be integrated onto the electrically heated ASRG Engineering Unit (EU) that required development of the generator interfaces and other design and process updates to meet the system requirements. In October 2007, Glenn delivered two ASC-E convertors plus a spare on schedule to DOE and Lockheed Martin for integration onto the ASRG EU. The ASRG EU successfully completed a variety of system-level demonstrations at Lockheed Martin followed by over 30,000 hr of extended operation at Glenn.

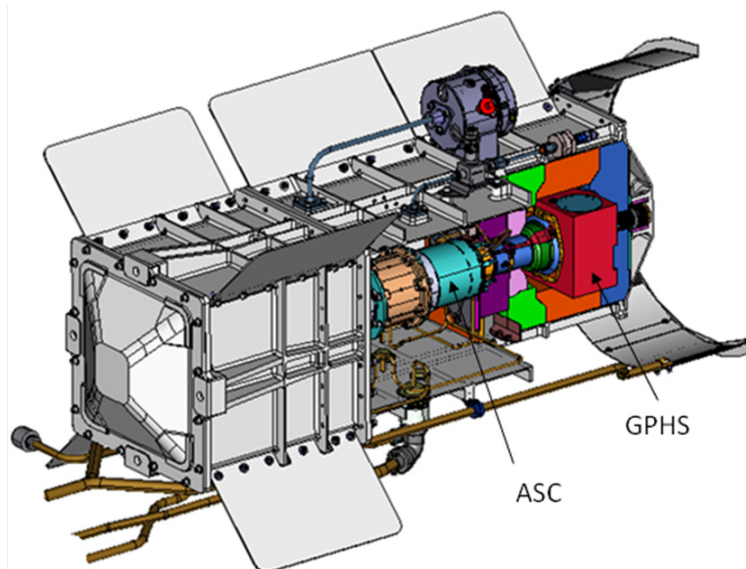


Figure 1.—Advanced Stirling Radioisotope Generator (ASRG) with two dual-opposed Advanced Stirling Convertors (ASCs).

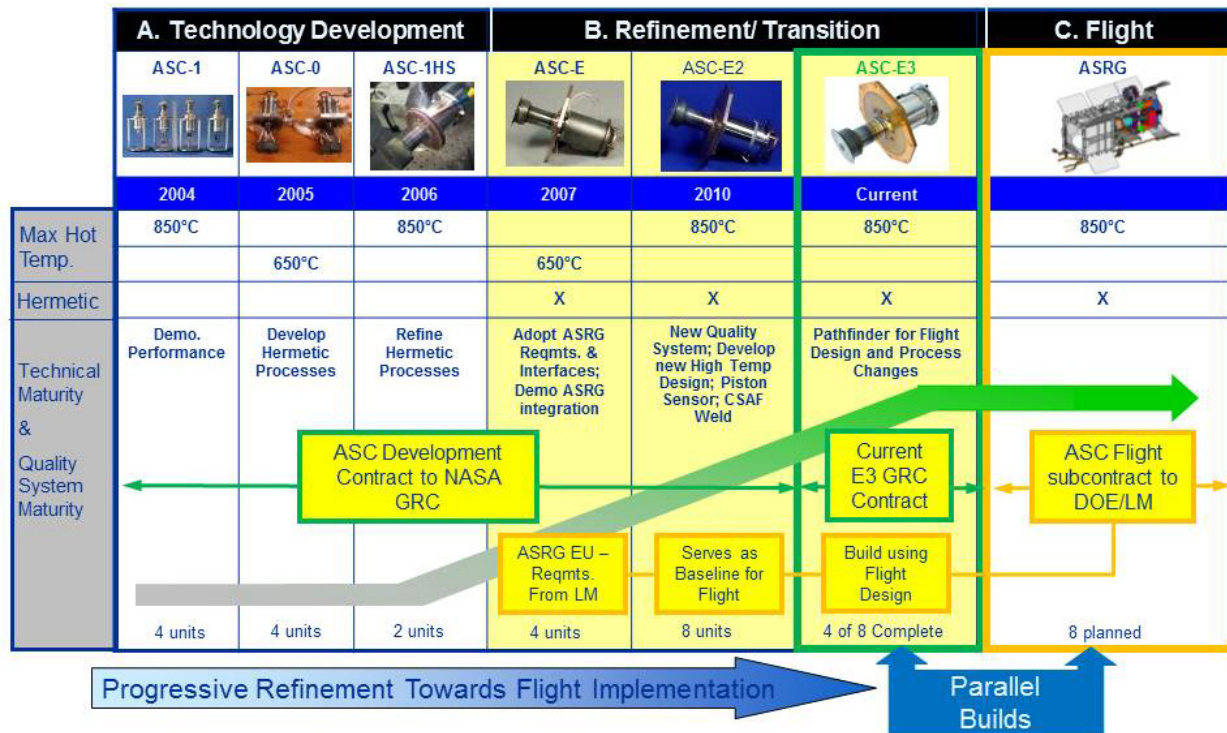


Figure 2.—Previous Advanced Stirling Convertor (ASC) Technology Evolution Strategy—Current Through October 2013.

While the ASC-E converters represented a major advancement of the technology, two additional generations of developmental ASCs, the ASC-E2 and ASC-E3, were planned to prepare for flight development to address evolving flight requirements, identification of design improvements, and a need to continue to mature the Sunpower quality system for flight hardware production. The second engineering unit design, the ASC-E2, was built under a new formal Quality Management System at Sunpower, and would implement several reliability-driven or anticipated flight-requirements-driven design changes. Specifically, the ASC-E2 required the development of a new heater head assembly design and manufacturing process making use of high-temperature nickel superalloy 247-LC that would allow 850 °C operation with long life and reliability. Glenn performed a variety of key technology support activities (Ref. 3) to mitigate risk including modeling and analysis, high-temperature metallic tests, organic materials tests, convertor vibration tests, convertor continuous extended operation, and reliability analysis. Sunpower completed and delivered eight ASC-E2 convertors to Glenn in 2010. To date, Sunpower has built and delivered 26 convertors under contract to Glenn across several designs. The convertors are used for extended-operation reliability testing, durability testing, and as support hardware for Lockheed Martin’s controller development. The overall ASC design evolution strategy that was in place until fall 2013 is illustrated in Figure 2.

Before the ASC-E3 engineering units were initiated under the NASA contract, Sunpower entered a parallel subcontract with DOE and Lockheed Martin for ASC-F flight development and production. A total of eight flight ASC-F units were planned with an initial pair to be used on the ASRG Qualification Unit, with two pairs used for two ASRG Flight Units, plus a spare pair of convertors. The circumstance motivated replanning so that the ASC-E3 would be produced from the flight ASC-F specification and design documentation. The first two pairs of ASC-E3s became production pathfinders to demonstrate processes, identify and resolve any production issues and nonconformances, and reduce risk ahead of the flight ASC-F production steps. Additionally, this new strategy provided NASA with flightlike ASC-E3

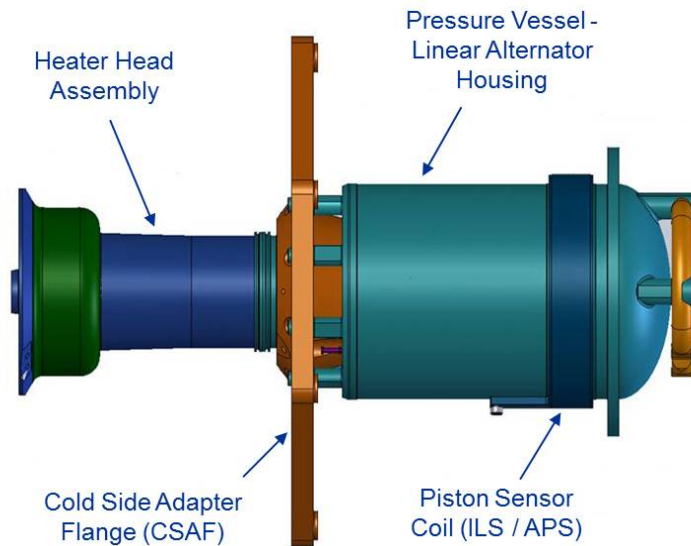


Figure 3.—Dedicated Advanced Stirling Converter (ASC) cleanroom at Sunpower.

convertors that could be used for extended operation and characterization tests to establish reliability of the flight design (Ref. 4). Further, in 2011 Sunpower relocated to a new facility that included a new cleanroom designed specifically for ASC flight hardware production (Ref. 5). The ASC–E3 Pair 2 was the first hardware to be processed using the cleanroom, pathfinding new production procedures that addressed the flight cleanliness requirements. The last two pairs of ASC–E3 were intended to be flightlike and identical to the flight units with the exception of flight certification. General layout of the ASC flight design is shown in Figure 3.

ASRG Integrated Flight Project

The integrated project included two standing boards at the lower ASC production level, the Joint ASC Configuration Control Board (CCB), and the ASC Material Review Board (MRB). Both boards had representatives from Lockheed Martin, DOE, and NASA Glenn with Sunpower personnel typically presenting to the boards. The Joint ASC CCB had the responsibility to review and approve all ASC–F design documentation including drawings, process specifications, process documents, and test procedures. As discussed earlier, the ASC–E3 being produced for Glenn uses the same ASC–F flight documentation, thus the joint CCB was an effective means of ensuring all design and production updates are agreed upon by all parties. The MRB was actually made of a flight ASC–F MRB and an ASC–E3 MRB that conducted reviews for the respective hardware at the same time, allowing mutual insight into nonconformances on both E3 and flight builds, yet allowing disposition authority for hardware to remain with the appropriate parties for whom the hardware was being built.

To support the management of the ASRG project, a continuous Glenn technical presence at Sunpower was established to manage, monitor, and provide insight into the ASC–E3, ASC–F, and ancillary tasks. This value-added onsite activity was achieved through technical rotations of 1-week duration consisting of four individuals familiar with ASC design, production, and testing including the ASC lead engineer, deputy ASC lead engineer, and two ASC cognizant test engineers that are responsible for ASC–E3 convertors after delivery. Similarly, Lockheed Martin also established a weekly rotation of onsite

personnel at Sunpower with varying project roles including the Certified Product Engineer, Task Lead, and Quality Assurance lead. The Glenn and Lockheed Martin personnel mix offered the desired skill set as Sunpower transitioned from the design phase and focused on ASC production and testing.

ASC–F Flight and ASC–E3 Accomplishments

During the parallel ASC–E3 and ASC–F builds, the integrated ASC team made numerous advancements toward flight hardware production. Highlights include the following:

New Sunpower Facility and Cleanroom

In order to meet flight production requirements, Sunpower relocated to a larger facility to accommodate the growing staff and increased and more rigorous production requirements for the ASRG flight project. Sunpower completed the relocation on schedule in July 2011. The primary driver for the relocation was the flight cleanliness and planetary protection requirements that necessitate convertor buildup and processing in a cleanroom environment (Figure 4). Sunpower’s facility includes dedicated lab space for convertor component processing, dedicated space for special processes, and testing capacity for a minimum of six convertors simultaneously.

The ASC cleanroom is an ISO Class 8 environment with ISO Class 5 laminar flow bench workspaces. The cleanroom has the capacity to process up to eight convertors simultaneously. Special processes within the cleanroom include convertor level inspection and processing, vacuum bakeout, cleanroom inspection, black light inspection, specialized subassembly cleaning processes, and final assembly. The ASC–E3 Pair 2 was the first set of convertors to be processed in the cleanroom. The ASC–E3 Pair 3, ASC–E3 Pair 4, and ASC–F Pair 1 (for Flight Qualification Unit) have also been processed in the cleanroom.



Figure 4.—Dedicated Advanced Stirling Convertor (ASC) cleanroom at Sunpower.

TABLE 1.—ADVANCED STIRLING CONVERTOR (ASC)
PRODUCTION DOCUMENTATION MATURITY

Document Type	Total	Approved
Drawings	124	124
Process Document	65	65
Process Specification	27	27
Test Procedure	37	37
Process Utilization List	50	49

Flight Production Documentation Maturity

A strategy of the ASC–E3 and flight parallel contracts was that a single set of flight production documentation would be used. In order to maximize lead time for ASC–E3 Pairs 1 and 2 pathfinders ahead of flight hardware processes, production documentation was required to be Sunpower released but was not required to be issued (i.e., fully approved jointly by Lockheed Martin, NASA Glenn, and DOE CCB) prior to use in ASC–E3 Pairs 1 and 2 production. However, a best effort was made to use issued documentation whenever available. In many instances, pathfinding provided by the ASC–E3 Pairs 1 and 2 production served as the final step in development of flight processing and documentation refinement. ASC–E3 Pairs 1 and 2 production closed nearly all open issues in production documents prior to the ASC–E3 Pair 3, ASC–E3 Pair 4, and all flight convertor processing. Pair 3, Pair 4, and all flight convertors were required to be processed to fully issued documentation. ASC production documentation is divided into five categories—drawings, process document, process specification, test procedure, and special processes. Table 1 presents the current status of ASC documentation. All production documents have been approved with the exception of one “Process Utilization List” item that was in the process of being approved at the time of ASRG termination. As needed, production documentation is revised and submitted to the CCB for approval as lessons learned in production are identified.

Flight Certified Quality System

Early in the flight project (December 2009), Sunpower successfully passed an ISO 9001:2000 compliance audit, which certified Sunpower’s quality system and approved Sunpower as a flight hardware provider. In September, 2011, after relocation to a new facility, Sunpower successfully passed a surveillance audit and recertification to ISO 9001:2000.

Key elements to building and certifying the quality system included establishing quality system governing plans and processes and developing in-house verification methods. Project-level plans such as the Quality Assurance Program Plan, Configuration Management Plan, Quality Assurance Inspection Plan, Software Management Plan, Contamination Control Plan, and Verification Plan were project-level deliverables that were reviewed and approved by the customer and set the project requirements for Sunpower. Key processes established include nonconforming material control, corrective and preventative action system, configuration management, and process qualification via the Process Utilization List. In-house verification methods included incoming material and product inspection, certified inspection of workmanship standards, and inspection to meet cleanliness requirements.

Regenerator Production Capabilities

Sunpower designers had worked with a Glenn materials specialist to develop the high-temperature, oxidation-resistant, high-porosity regenerators used in the ASC design. Once production methods were established and hardware demonstrated, it was desired to transfer regenerator production responsibility to Sunpower. This was done slowly in stepwise fashion including training and review of resultant

regenerators produced at Sunpower. Transferring production to Sunpower was viewed as a minimal risk and a necessary step for securing future convertor production as the production process was developed in a research laboratory at Glenn not intended for high-volume flight production. Sunpower established a duplication of Glenn’s regenerator production capabilities in the new facility and successfully produced all ASC–E3 and ASC–F regenerators.

New Mechanical Joint for CSAF

During production of the ASC–E3, technical issues were identified related to bonding of the cold-side adapter flange (CSAF) (Figure 5) that provides structural support and provides heat rejection from the ASC to the generator housing. A mechanical press fit joint with supplemental fasteners between the CSAF and the “transition assembly” hub of the ASC was established to replace the metallurgical joint. The new mechanical joint was demonstrated to meet all performance and structural requirements through component thermal vacuum testing, convertor operation, and qualification-level vibration testing, so it was adopted on the ASC–E3/ASC–F design.

Heater Head Nondestructive Inspection

A Heater Head Technical Product Team completed the assessment of the small casting defects that may exist in the heater heads. Through material tests, component tests, structural modeling and analysis, and multiple high-level vibration tests, the team concluded that the nondestructive evaluation of each finished heater head using microfocus x-ray computed tomography and high-temperature helium leak testing is sufficient to screen for any critical defects, ensuring all heater heads used on ASCs meet design requirements (Ref. 6).

Cylinder Assembly Improvement

Production issues were encountered for the critical cylinder assemblies that define the bore in which the piston and displacer reciprocate. The issue was resolved over the course of several months by a dedicated working group leading to improvements in heat treatment of the cylinder stock material, improved dimensional control at the component and assembly level, and improved process for bonding the assembly. The issue was resolved and convertor production with acceptable cylinders continues. In parallel, trials have shown a significant increase in production yield and manufacturability when implementing the recommendations of the working group.

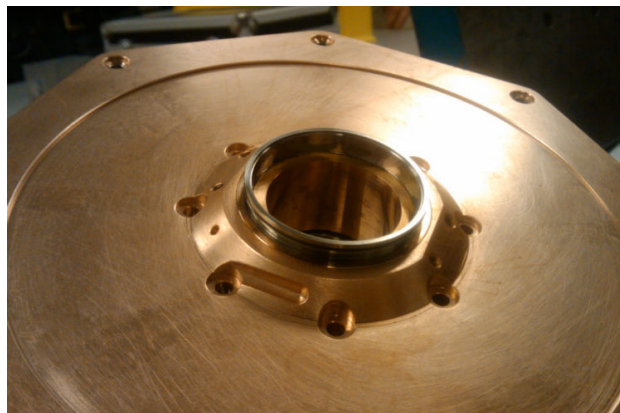


Figure 5.—Cold-Side Adapter Flange (CSAF) attached to Advanced Stirling Convertor (ASC) transition assembly.

Improvements in Sunpower ASC Operational Testing

Many significant improvements were made in ASC testing throughout the ASC–E3 and ASC–F projects. Improvements were developed by the testing team led by NASA Glenn personnel that included Sunpower and Lockheed Martin staff in response to project needs for higher fidelity test data and test standardization to minimize inaccuracies and miscommunication. The team included testing, engineering, manufacturing, technician, and quality disciplines. Standardizing test methodologies and terminology and increasing accuracy and repeatability of tests at all locations provided significant benefits as discussed below.

Common Performance Hardware

An improvement in testing ASCs is the adoption of a new “common performance hardware” design that is used for all performance verification and performance mapping tests at Sunpower and Glenn. The common performance hardware includes the integrated insulation, electric heaters, thermocouples, and structural support for the test. It minimizes overall heat leaks and reduces variability in test data based on test setup teardowns and test location. The use of the setup also allows for more accurate and repeatable modeling of the net heat input to the convertor, a key parameter to establish the performance of each ASC (Ref. 7). Additionally, each ASC–E3 is delivered installed in the common performance hardware allowing Glenn to perform independent performance verification tests using the same physical test configuration as was tested at Sunpower prior to delivery, further minimizing data variability. The test configuration for ASC–E3 Pair 1 as assembled at Sunpower, then installed at Glenn is shown in Figure 6.

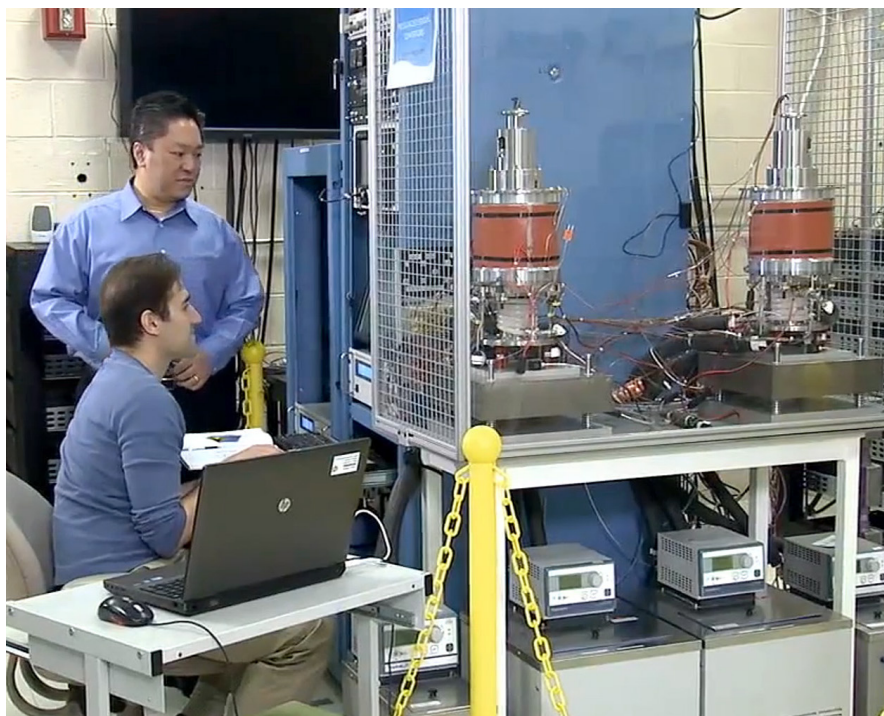


Figure 6.—Advanced Stirling Convertor (ASC)–E3 Pair 1 (#1 and #2) in individual common performance hardware under vertical performance testing at NASA Glenn Research Center Stirling Research Laboratory.

Test Software

Primarily developed by the NASA Glenn test team, the Labview test software employed at Glenn and Sunpower has been standardized and placed under configuration control. The program is written specifically for ASC testing with control screens and graphical interface options that are tailored to the user location but available for use by all operators. For example, Sunpower tests are focused on some different indicators and data since the convertors spend most of their processing in a nonhermetic form. Thus, Sunpower uses a tailored control screen. For purposes of troubleshooting and communication, the same screen is available on all NASA Glenn test racks. Additionally, the Sunpower data capture rates have been improved in the software to allow more detailed analysis of test data at the 2-sec sampling rate and kilohertz rate for some parameters.

Unattended Convertor Operation

A capability added to the Sunpower test rack that has made a significant impact is unattended operation. The controls and safeties used for unattended operation were developed over years of continuous extended operation testing across many different convertors at Glenn. In addition to the software controls, Glenn provided Sunpower with fail-safe protection circuits. With unattended operation, convertors can test 24 hr per day/7 days a week with alarms programmed to safely shut down convertors if their performance is outside of programmed allowables. With unattended operation, Sunpower's production cycles can be reduced by eliminating some of the warmup and cooldown cycles during testing, each of which can span 1 to 2 hr per day.

Horizontal Operation With Clocking

While prior convertor production testing included limited horizontal operation, and some post-delivery testing at Glenn was done horizontally, in order to improve characterization of the ASCs in multiple orientations, the test team developed a fixture that allowed convertor in nonhermetic production stages to be operated horizontally in multiple clockings. On the ASC-E3 Pair 3, a newly configured shakedown test sequence was implemented that allowed testing to occur in four clocked, horizontal positions at all reference test conditions without breaking configuration and without stopping the convertor to change orientation.

First Operation of ASC-F Flight Convertors

In June 2013, Sunpower operated for the first time an ASC-F that was built to the rigors of flight production and quality requirements. The initial pair of ASC-F was allocated for integration on the ASRG Qualification Unit that would have been fueled and subjected to rigorous system-level tests. These initial flight units were undergoing shakedown testing when flight contract termination stopped all work on them, and the convertors were secured in storage. The convertors are being transferred to the Glenn ASC contract although no decisions have been made yet in terms of what will be done with these units.

Delivery of ASC-E3 Pair 1 and Pair 2

In November 2012, Sunpower completed and delivered to Glenn the first ASC-E3 "pathfinder" pair. Figure 7 shows ASC-E3 #2 while it was still early in its production stages, prior to heater head and photovoltaic welds. As expected, there were many lessons learned and production issues uncovered that were resolved, reducing risk to the production of later flight convertors. ASC-E3 Pair 1 generally followed flight production requirements except for assembly in the cleanroom. ASC-E3 Pair 2 convertors

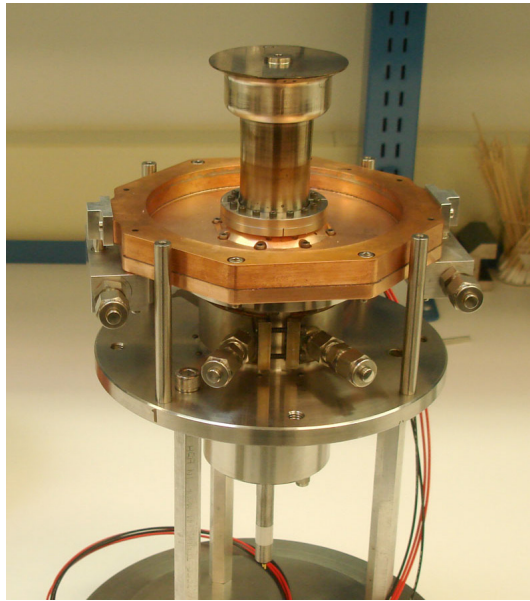


Figure 7.—In-process nonhermetic configuration Advanced Stirling Convertor (ASC)-E3 #2.

were the pathfinders for cleanroom production. While it is typical for pairs to have parallel production throughout, Pair 2 did not and as a result, ASC-E3 #4 was delivered to Glenn in August 2013 and ASC-E3 #3 was delivered in November 2013.

All ASC-E3 Pairs 1 and 2 convertors met performance specification at Sunpower and later at Glenn during independent verification tests. E3 Pair 1 was configured in a dual-opposed configuration, completed supporting ASRG controller testing at Lockheed Martin Coherent Technologies. Pair 1 has been returned to Glenn and is currently being integrated into the ASRG EU #2 generator for system-level testing.

NASA Glenn ASC Testing

Glenn's Stirling Research Laboratory (SRL) was established in 1999 and has expanded as additional convertors became available and additional space was required. The primary function of the SRL is to test Stirling convertors and generators, typically in unattended extended-operating mode. The SRL has developed test capabilities and methods that allow safe continuous operation of high value hardware that provides autonomous safe shutdowns if any faults are detected. The SRL also has a dedicated thermal vacuum facility that allows operation of Stirling systems in a relevant environment. Design, buildup, and maintenance of the control systems, data systems, long-life electric heat sources, and ancillary facility support systems are also SRL responsibilities.

Establishing life and reliability of the ASC technology has been imperative. Many activities including modeling, structural analysis, metallic and organic material evaluations, component testing, convertor vibration and durability testing, and reliability modeling have been completed by Glenn to assess the reliability and margins of the ASC design. The continuous extended operation of ASCs and generators in the SRL plays a central role in establishing the reliability of Stirling systems. Table 2 shows the accumulated operating hours for select ASCs at Glenn. ASC-0 #3, an early laboratory demonstration convertor is the unit leader for accumulated operating time with almost 45,000 hr (over 5 years). ASC-E3 #4 is the flightlike convertor that has nearly 5,000 hr. In total, the cumulative operating hours for all ASCs at Glenn is over 316,000. Meanwhile, additional test racks and space is being prepared for testing of the additional flightlike ASC-E3 Pairs 3 and 4, planned for delivery August 2014 and early 2015, respectively.

TABLE 2.—NASA GLENN ADVANCED STIRLING CONVERTOR (ASC)
OPERATING HOURS AS OF JULY 7, 2014

Convertor(s)	Hour	Comment
ASC-0 #3	44,939	Single ASC Leader
	119,728	Total: Early Technology Demonstration ASCs
ASC-E #2	35,316	Previously in ASRG Engineering Unit (EU)
ASC-E #4	32,248	Adopted some E2 changes
ASC-E2 #4	13,568	
ASC-E2 #5	27,316	
	181,451	Total: Transition to Flight ASCs
ASC-E3 #1 and #2	3,109 and 3,104	Preparing for ASRG EU2 installation
ASC-E3 #3 and #4	3,970 and 4,939	First units produced in cleanroom
	15,122	Total: Flight pathfinder ASCs
Total ASC	316,301	Includes All Prior ASC Units

ASC Status and Path Forward

In late fall 2013, the DOE initiated termination of the Lockheed Martin ASRG flight contract, driven primarily by budget constraints. As a result, Sunpower’s subcontract for the flight development of ASC-F was also terminated. NASA continues to recognize the importance of high-efficiency Stirling power conversion for RPS and continues investment in the technology. The Stirling effort is being reformulated currently under the SRG technology development task. Immediate project objectives include completion at Sunpower of the remaining ASC-E3 Pairs 3 and 4 convertors. Additionally, Glenn is assembling an ASRG EU #2 (EU2), the highest fidelity flightlike Stirling generator built to date that will integrate Sunpower’s flightlike ASC-E3 Pair 1, Lockheed Martin’s functionally flightlike EDU4 controller, and Glenn’s aluminum flightlike housing that will enable a variety of key system-level and interface evaluations. Meanwhile, SRG planning is underway to develop a longer-term path forward to continue NASA Stirling RPS development. The status of flight contract termination, progress made on ASC-E3 Pairs 3 and 4 as well as EU2, and outlook for Stirling RPS are summarized below.

ASC Flight Contract Termination Status

On November 13, 2013, Sunpower received notice of termination of the ASC-F contract as a result of budgetary constraints within NASA. As of May 2014, all Sunpower flight closeout activities are complete with the exception of the final administrative closeout which is expected to occur in fall of 2014 when Lockheed Martin’s prime contract is closed.

Hardware Transfer to ASC-E3 Contract

At the direction of the integrated Federal project, and in order to not adversely affect ASC-E3 production under the ongoing technology development contract with Glenn, Sunpower was granted continued access to all common inventory hardware and all tools, fixtures, etc., that were needed for production and were previously shared by the contracts. In parallel, and in accordance with termination requirements, Sunpower began preparing a “termination inventory” of all flight-owned assets. In recognition of the ASC-E3 and flight project dependence on common inventory, the integrated Federal project directed DOE, Lockheed Martin, and Sunpower to identify all hardware needed for ASC-E3 Pairs 3 and 4 production and expedite their transfer to the ASC-E3 project. All other lower priority flight assets at Sunpower, including the ASC-F flight convertors, are also being transferred to the Glenn

contract although no programmatic decisions have been made about usage of the flight convertors and subassemblies at this time.

Closeout of Open Nonconformances (NCR)

At termination, there were several flight NCRs with open hardware disposition and/or preventative and corrective actions. For all NCRs relating to hardware that would be transferred to the ASC–E3 contract, the NCRs were administratively closed and then reopened under an ASC–E3 MRB NCR. Those NCRs that would be transferred to future projects were administratively closed and added to the ASC–F lessons learned log for tracking. Any remaining NCRs were administratively closed without transfer.

Continued ASC–E3 Production at Sunpower and ASRG EU2 Assembly at NASA Glenn

While ASC–E3 Pair 3 was already in production at the time of ASRG termination, a result of termination was replanning for ASC–E3 Pair 4. Originally, the production sequence was for the eight flight ASC–F convertors to follow ASC–E3 Pair 3 giving flight hardware priority, followed by ASC–E3 Pair 4. With termination of the flight contract, E3 Pair 4 was accelerated and production was started earlier than planned. ASC–E3 Pair 3 convertors made excellent production progress, and they have been completed including hermetic sealing (Figure 8). They are undergoing final performance testing and a hardware acceptance review is planned for August 2014 with delivery to Glenn anticipated about a month ahead of schedule. ASC–E3 Pair 4 front end assembly was completed and initial operation was achieved February 2014. The Pair 4 convertors are going through shakedown testing and have completed heater head weld and pressure vessel sleeve weld and delivery is expected in early 2015.

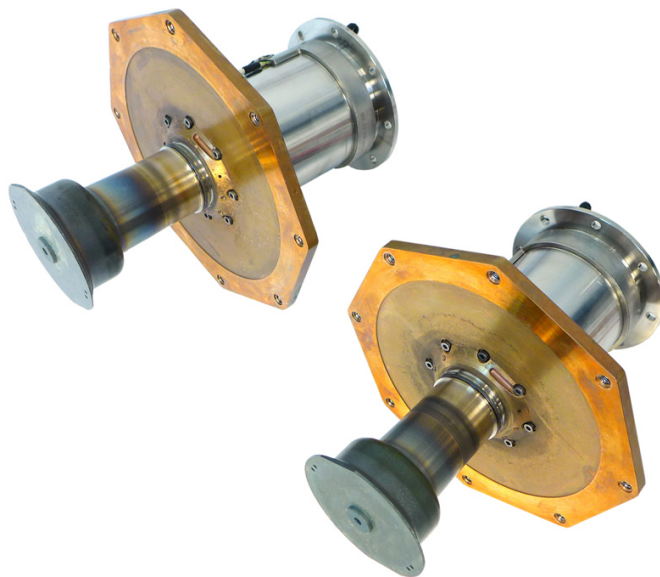


Figure 8.—Completed flightlike Advanced Stirling Convertor (ASC)–E3 Pair 3 convertors.

A priority for the SRG task is the completion of the ASRG EU2 utilizing the ASC–E3 Pair 1, the Lockheed Martin controller, and a flightlike aluminum generator housing assembly (GHA). The high-fidelity ASRG EU2 will be used for system-level performance assessment and characterizations, validation of various interfaces and system requirement, and ASC extended operations within the EU2. These key system-level activities will provide data and guidance for future Stirling systems. After delivery to Glenn, ASC–E3 Pair 1 convertors completed independent performance verification testing, performance mapping, and unattended operation. The units were then provided to Lockheed Martin for successful controller functional testing (Ref. 8). The units have been returned to Glenn, have completed receipt checkout tests, and are being prepared for integration into the ASRG EU2. The ASC–E3 Pair 1 convertors have each accumulated over 3,100 hr of operation at Glenn with steady flat-line performance.

Glenn has awarded a contract to Lockheed Martin to complete the production and delivery of the EDU4 controller which is expected fall 2014. Meanwhile, the Glenn GHA has been completed and various practice assembly trials have been performed. The ASC–E3 Pair 1 convertors have completed dual-opposed integration with each other via the interconnect tube. As of this writing, ASRG EU2 assembly (Figure 9) is making good progress and plans are to operate the system, without the Lockheed Martin controller by September 2014. Operations with the controller along with a suite of ASRG EU2 tests are planned for 2015 to 2016 (Ref. 9).

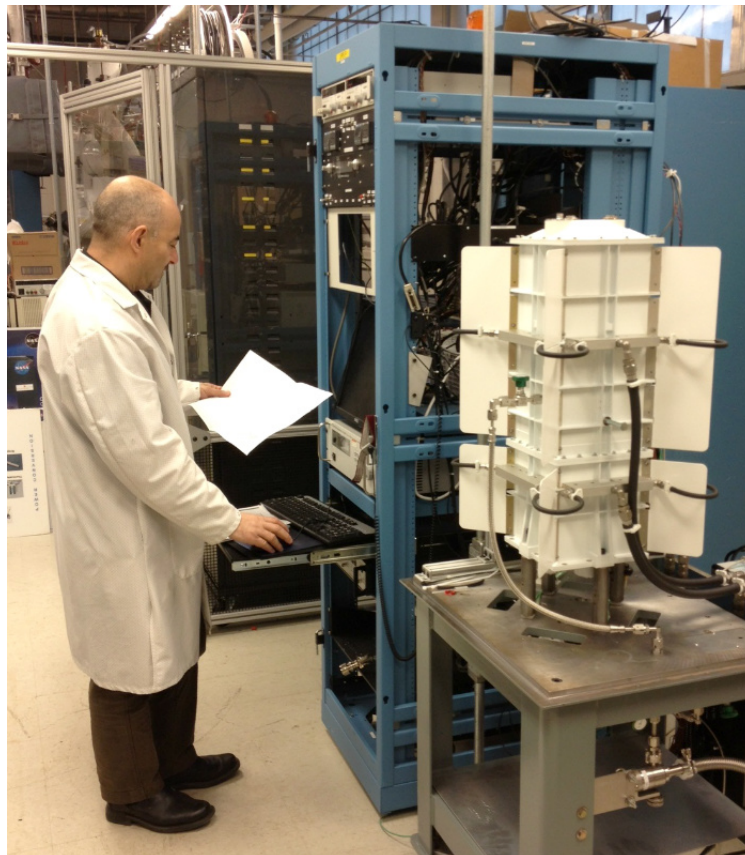


Figure 9.—Advanced Stirling Radioisotope Generator (ASRG) Engineering Unit 2 (EU2) flightlike housing fit check and preparations.

Options for Stirling RPS Path Forward

High-efficiency Stirling power conversion for RPS continues to be a priority for NASA's Science Mission Directorate given the low plutonium fuel inventory in the United States and relatively low planned fuel production rate. In parallel with the lower 140-W-class ASRG, NASA's Space Technology Mission Directorate has also been sponsoring the development of higher power Fission Power Systems (FPS) including the development of the Sunpower 12-kW Stirling Power Conversion Unit (PCU) (Ref. 10). The PCU is planned for delivery to Glenn this fall for integration into the fission Technology Demonstration Unit (TDU) for electrically heated system demonstration of key FPS technologies in Glenn's Vacuum Facility 6 in 2015. Sunpower has developed a range of high-efficiency power converters that share common technologies and basic configuration with the 80-W ASC including the 35-W SBIR unit, a 1-kW convertor, and the 12-kW PCU (6 kW per dual opposed piston/alternator). Figure 10 illustrates the family of power pistons for each of these four converters. Given the scalability of the ASC technology, the power level for any future Stirling RPS is being reconsidered with options of increasing the power of the Stirling convertor based on increments of GPHS modules used with 250 W of thermal output per module.

To help guide SMD RPS investments as well as FPS development, a Nuclear Power Assessment Study (NPAS) has been chartered to evaluate the relevant technologies for RPS and FPS, fuel availability, candidate system configurations and power levels, and reference candidate missions. The NPAS Team is expected to complete the study in fall 2014 with recommendations for RPS and FPS path forward. In particular, the team will be assessing common technology approaches that may be applicable to both RPS and FPS.

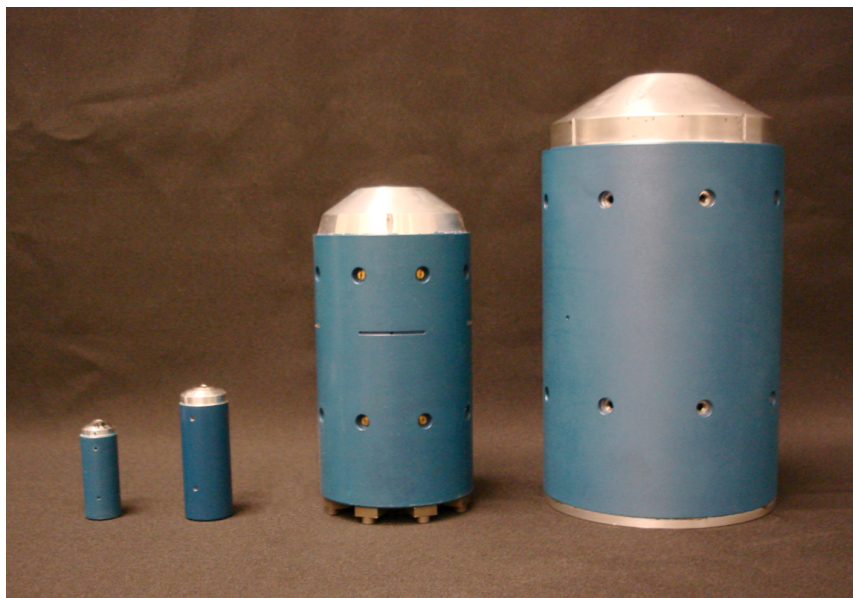


Figure 10.—Scaled Advanced Stirling Converter (ASC) technology—pistons from existing Sunpower converters, left to right: 35-W Small Business Innovative Research (SBIR), 80-W ASC, 1-kW convertor, and 6-kW piston (two used for the 12-kW Power Conversion Unit (PCU)).

While no decisions on Stirling RPS path forward have been made as of this writing, programmatic interest in the high-efficiency ASC technologies continues to be high given the limited fuel availability. It is anticipated that ASC–E3 Pair 3 and 4 convertors will be completed and delivered, the ASRG EU2 will complete integration and system-level tests, and the Glenn SRL will continue to operate the ASCs to expand the reliability database. A consideration for planning is the availability of ASC flight assets including ASC–F convertors that were in production, subassemblies, and many components in bonded-storage, all of which are being transferred to the Glenn ASC contract. While the ASRG flight development contract was terminated, and future Stirling RPS designs may be different from the ASRG, the Stirling-related technologies and engineering that have made significant advancements during the course of the ASRG project will likely continue to be applicable to future systems.

Summary

Breakthrough high efficiency demonstrated by Sunpower using the early Advanced Stirling Convertors (ASCs) led to the expansion of the NASA Glenn Research Center technology development project, and the adoption of the technology as part of the Department of Energy (DOE) and Lockheed Martin Advanced Stirling Radioisotope Generator (ASRG) flight development contract. Significant progress was made by the ASRG integrated flight project team to the point that the technology was on the cusp of a launch opportunity. While not selected, the ASRG was proposed as the power system for two of the three Discovery 12 candidate missions, Titan Mare Explorer (TiME) and Comet Hopper (CHopper). With the termination of the ASRG contract, NASA and its partners are reevaluating technology availability, capabilities, and mission requirements in an effort to identify a path forward for sustainable, reliable, and affordable nuclear space power systems. As limited availability of plutonium-238 fuel continues to be a driver, high-efficiency Stirling technology remains essential for future NASA Radioisotope Power Systems (RPS).

References

1. Wong, W.A.; Anderson, D.J.; and Tuttle, K.L.: Status of NASA's Advanced Radioisotope Power Conversion Technology Research and Development. Proceedings for Space Technology and Applications International Forum (STAIF–2006) (NASA/TM—2006-214243), Albuquerque, NM, 2006.
2. Wong, W.A.; Wood, L.G.; and Wilson, K.: Advanced Stirling Convertor (ASC)—From Technology Development to Future Flight Product. Proceedings for Space Technology and Applications International Forum (STAIF–2008) (NASA/TM—2008-215282), Albuquerque, NM, 2008.
3. Schreiber, J.G.; Thieme, L.G.; and Wong, W.A.: Supporting Technology at GRC to Mitigate Risk as Stirling Power Conversion Transitions to Flight. Sixth International Energy Conversion Engineering Conference (IECEC–2008) (NASA/TM—2009-215515), AIAA, Cleveland, OH, 2008.
4. Wong, W.A., et al.: Pathfinding the Flight Advanced Stirling Convertor Design with the ASC–E3. Tenth International Energy Conversion Engineering Conference (IECEC–2012) (NASA/TM—2014-217753), AIAA, Atlanta, GA, 2012.
5. Collins, J., et al.: Sunpower's Dynamic Conversion to Flight with the Advanced Stirling Convertor (ASC–F). Tenth International Energy Conversion Engineering Conference (IECEC–2012), AIAA, Atlanta, GA, 2012.
6. Wilson, S.D.; and Wong, W.A.: NASA Glenn Research Center Support of the ASRG. Twelfth International Energy Conversion Engineering Conference (IECEC–2014), AIAA, Cleveland, OH 2014.

7. Wilson, S.D., et al.: Overview of Heat Addition and Efficiency Predictions for an Advanced Stirling Converter. Ninth International Energy Conversion Engineering Conference (IECEC–2011) (NASA/TM—2012-217292), AIAA, San Diego, CA, 2011.
8. Chan, J., et al.: System-Level Testing of the Advanced Stirling Radioisotope Generator Engineering Hardware. Twelfth International Energy Conversion Engineering Conference (IECEC–2014), AIAA, Cleveland, OH 2014.
9. Lewandowski, E.J.; Bolotin, G.S.; and Oriti, S.: Test Program for Stirling Radioisotope Generator Hardware at NASA Glenn Research Center. Twelfth International Energy Conversion Engineering Conference (IECEC–2014), AIAA, Cleveland, OH, 2014.
10. Stanley, J., et al.: Progress in the Development of a 12kWe Stirling Power Conversion Unit for Fission Power Systems. Proceedings of the Nuclear and Emerging Technologies for Space 2013 Conference (NETS–2013), Albuquerque, NM, 2013.

