CONTINUING DEVELOPMENT OF THE ADVANCED STIRLING CONVERTOR (ASC) FOR NASA RPS

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Background: Sunpower's 80-watt class Advanced Stirling Convertor (ASC) initiated development under contract to NASA Glenn Research Center (GRC) and after a series of successful demonstrations, the ASC began transitioning from technology development to flight development. The ASC technology provides very high thermal-to-electric conversion efficiency making it ideal for future Radioisotope Power Systems (RPS). The high efficiency Stirling system reduces fuel requirements by a factor of four compared to current thermoelectric systems, lowering system mass and enables more NASA Science missions given the small plutonium inventory in the U.S.

The strategy to develop the ASC technology under the NASA contract included multiple builds, each of which addressed objectives to evolve the technology in preparation for flight production. Each successive build includes design and processing changes to meet newly defined requirements, improve manufacturability, or enhance reliability. Early technology demonstrators (ASC-1, ASC-0, and ASC-1HS) demonstrated the high efficiency, small size, and low mass of the basic ASC design and allowed for the development of weld joint designs needed for hermetic sealing of the convertors. Additionally, testing of these early prototypes at both Sunpower and GRC allowed the identification of design improvements and development of test and processing techniques necessary for extended operation of ASC convertors.

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 Department of Energy and Lockheed Martin Advanced Stirling Radioisotope Generator (ASRG). The first generation ASC Engineering Unit (ASC-E) was developed by Sunpower and GRC working collaboratively with Lockheed Martin with the objective of defining requirements and developing the interfaces between the ASC and the generator system. In October 2007, GRC delivered two ASC-E convertors plus a spare on schedule to DOE/Lockheed Martin for integration onto the ASRG EU, which successfully completed a variety of system level demonstrations followed by over 30,000 hours of extended operation at GRC.

While the ASC-E convertors represented a major advancement of the technology, two additional generations of ASC convertors were planned to prepare for flight production to address evolving flight requirements, identification of design improvements, and a need to continue to mature the quality system at Sunpower. 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 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 that would allow 850°C operation with long-life and reliability. Sunpower completed and delivered eight ASC-E2 convertors to GRC in 2010 for extended operation and durability testing. The last engineering unit design, the ASC-E3, is currently being produced by Sunpower in parallel with flight convertors and they are the subject of the rest of this paper.

Flight Hardware and Engineering Unit Parallel Production: In recent years, the ASC became part of the NASA-Department of Energy ASRG integrated Federal Project. Sunpower held two parallel ASC contracts, one with the Department of Energy/Lockheed Martin to produce four pairs of flight ASC-F convertors, and one with NASA GRC for the production of four pairs of the ASC-E3 engineering unit (Figure 1). The development strategy was to build ASC-E3s using the ASC-F flight specification, design and production documentation. This allowed the first two pair of earlier ASC-E3 to serve as production pathfinders to identify issues and allow timely resolution well ahead of flight hardware production. This also provided NASA with four pairs of flight representative ASC-E3 that would be used for independent validation and verification performance testing, extended reliability testing, and system level interface and interaction evaluations.

Figure 1. First Pair of flight-like ASC-E3 Engineering Unit.

ASC-E3 and ASC-F Accomplishments: During the parallel ASC-E3 and ASC-F production, the integrated ASC team has made numerous advancements toward flight hardware production. Highlights include:

New Sunpower Facility and Clean Room. 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. One of the primary drivers for the relocation is the flight cleanliness requirements that necessitate build-up and processing in a clean room environment. The ASC-E3 Pair 2 is the first set of convertors to be processed in the clean room.

New Mechanical Joint for CSAF. During production of the ASC-E3, technical issues were identified related to welding of the Cold Side Adapter Flange that provides structural support and provides heat rejection from the ASC to the generator housing. A mechanical press fit joint was designed to replace the weld joint and the joint was demonstrated to meet all performance and structural requirements including qual-level vibration testing and adopted on the E3 and F design.

Heater Head Castings. A Heater Head Technical Product Team completed the assessment of the small casting oxides 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 non-destructive 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.

Cylinder 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 leading to improvements in heat treatment of the stock material, improved dimensional control at the component and assembly level, and improved process for bonding the assembly. The issue was resolved and production with acceptable cylinders continues.

Operational Improvements with Common Test Setup. An improvement in testing ASC convertors is the adoption of a new "common test setup" design that is used for all performance mapping tests at Sunpower and GRC. The common test setup minimizes overall heat leaks, and reduces variability in test data based on test setup tear-downs and test location. The use of the setup also allows for more accurate and repeatable assessment of performance of each convertor.

First operation of ASC 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 are allocated for integration on the ASRG Qualification Unit for rigorous system level tests.

Completion and Delivery of ASC-E3 Pair 1 and Pair 2. In 2013, Sunpower completed and delivered to GRC the four ASC-E3 "pathfinder" convertors. By intent, there were many lessons-learned and production issues uncovered that were resolved, reducing risk to the flight project. ASC-E3 Pair 1 generally followed flight production requirements except for assembly in the clean room. ASC-E3 Pair 2 was the pathfinder for clean room production. Both pairs met performance specification at Sunpower and later at GRC during independent verification tests. Pair 1 has been configured in a dual-opposed configuration and has been provided to Lockheed Martin Coherent Technologies to support ASRG controller testing.

ASC and ASRG Status: In late Fall 2013, the DOE initiated termination of the Lockheed Martin flight ASRG 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. The Stirling effort is being reformulated currently under the Stirling Radioisotope Generator (SRG) Project. Two immediate project objectives include completion at Sunpower of the remaining ASC-E3 Pair 3 and Pair 4 convertors by end of 2014. Additionally, GRC will be assembling an ASRG Engineering Unit #2 that will integrate Sunpower's ASC-E3 Pair 1, Lockheed Martin's EDU4 controller, and GRC's aluminum flight-like housing that will enable a variety of key system level and interface evaluations. Meanwhile, SRG planning is underway to develop longer-term path forward to continue NASA Stirling RPS development.

Figure 2. Aluminum Flight-like Housing for ASRG EU2 that will use ASC-E3 Pair 1.