SUMMARY OF ADVANCED STIRLING CONVERTOR (ASC) TESTING AT NASA GLENN RESEARCH CENTER. N. A. Schifer, S. M. Oriti, NASA Glenn Research Center, 21000 Brookpark Rd, Cleveland, OH.

Introduction: The Thermal Energy Conversion Branch at NASA Glenn Research Center (GRC) has been supporting the development of Sunpower's Advanced Stirling Convertor (ASC) for potential use in a Radioisotope Generator (ASRG) since 2003. A key area in which GRC has supported the ASC development is by providing independent verification and validation of convertor performance and reliability. GRC has established a Stirling test laboratory for continuously testing several ASCs for many thousands of hours to demonstrate long term performance and to develop the life and reliability database. There are currently six ASC convertors operating in continuous unattended mode, representing various stages in the developmental history of the ASC. A total of 25 ASC units have been operated at GRC with more than 293,000 hours (33.5 years) of total operation. Table I summarizes on-going ASC testing at NASA GRC.

Table I. **Summary of on-going ASC operation at NASA GRC as of January 2014.**

Convertors	Nominal Operating Power & Temperatures (We, Hot/Cold °C)	Date Initiated	Per-convertor runtime (hrs)
ASC-0 #3	75, 650/90	Aug 2007	40,500
ASC-E #4	65, 650/70	Dec 2009	28,000
ASC-E2 #4	80, 850/50	Aug 2010	9,700
ASC-E2 #5	80, 850/50	Aug 2010	23,400
ASC-E3 #1 & #2	80, 760/38	Nov 2012	3,000
ASC-E3 #3	80, 760/38	Nov 2013	825
ASC-E3 #4	80, 760/38	Aug 2013	1,790

Extended Operation Testing: The earliest design of the operating units, ASC-0 convertors, nominally produce approximately 75 W_e at operating temperatures of 650 ^oC hot-end and 90 ^oC cold-end. A total of four of these units were produced and have a total runtime of 97,500 hours (11.1 years). One of these units, ASC-0 #3, remains on continuous operation with over 40,500 hours (4.6 years) of operation.

A total of four ASC-E units were developed for NASA for integration into the first integrated generator system called the Advanced Stirling Radioisotope Generator Engineering Unit (ASRG EU). These convertors were the first fully hermetic units and nominally produce 65 W_e at operating temperatures of 650 ^oC hot-end and 70 ^oC cold-end and two of the units were integrated into the ASRG EU. Total combined runtime for these units is 104,400 hours (11.9 years). Currently, the ASC-E #4 continues to operate with more than 28,000 hours (3.2 years) of operation.

The ASC-E2 convertors were the first hermetic 850 ^oC design produced. A total of eight E2 convertors were produced, where two units were fitted with a removable alternator housing and intended for durability testing. Total combined runtime for these units is 63,800 hours (7.3 years). Currently, ASC-E2 #4 and #5 continue to operate in a dual opposed configuration with more than 9,700 and 23,400 hours (1.1 and 2.7 years), respectively. The ASC-E2 produced about 80 We while at the nominal operating temperatures of 850 ^oC hot-end, 50 ^oC cold-end, and 60 ^oC alternator housing temperatures; however, #4 and #5 are currently operating at the E3 beginning of mission low rejection specification producing 79 W_e at temperatures of 760 ^oC hot-end, 38 ^oC cold-end, and 46 ^oC alternator housing condition.

The latest ASC engineering units, the ASC-E3s, are being built using the flight design with the intent to pathfind the fabrication process that would be used for ASRG flight unit convertors and gain operational data from the earlier ASC-E3s. For this reason it is most important to accumulate operating hours on the ASC-E3 since these units will give the most representative reliability data for a flight generator. A total of eight hermetically sealed ASC-E3 units, capable of 850 ^oC maximum hot-end, are planned to be built. The E3 test sequence at GRC includes: 1) receipt/inspection/installation, 2) piston centering characterization, 3) insulation loss characterization, 4) performance mapping, 5) extended performance mapping, and 6) extended operation. The receipt process is a procedure to inspect the shipment and setup the convertors on the test stand. The piston centering characterization test serves to characterize the power required to move the piston through its full range of motion for use when performing the centering process. The insulation loss procedure is used to characterize the thermal losses through the insulation to enable calculation of the net heat input for use in performance verification. The performance mapping stage consists of an independent verification of convertor performance at seven operating conditions defined in the ASC product specification. These seven points bound the operating conditions expected during mission life including beginning of mission (BOM), end of mission (EOM), low rejection (LR), high rejection (HR), max qual, min qual, and max temp. The measured performance at GRC is compared to both the ASC production specification and to Sunpower generated performance data. Extended performance mapping consists of a test matrix of 36 interstitial test conditions, which gives a more comprehensive performance map [1].

The first pair of ASC-E3s (#1 and #2) were delivered to GRC in November 2012 and have each accumulated more than 3,000 hours of operation. The first pair of ASC-E3 convertors completed the first five stages of the described test sequence and had begun stage six prior to shipment to Lockheed Martin (LM) to support controller qualification testing. The independent performance tests at GRC showed that both convertors met the performance specification for all seven reference points, and matched the results from Sunpower within 3% in most cases. In addition, the GRC and Sunpower results from the extended performance map indicated agreement in power output within 2% for nearly all 36 points. ASC-E3 1st pair is expected to return from LM in the second quarter of 2014, at which time the convertors will be integrated into a flight-like generator housing and will be called Engineering Unit #2. This will enable system-level tests without production of a qualification unit, which reduces cost and complexity [2].

ASC-E3 #4 was delivered to GRC in August 2013 and has accumulated more than 2,000 hours of operation. This convertor has completed the first five stages of the test sequence and has begun extended operation. A plot of convertor performance is shown in Figure 1 below.

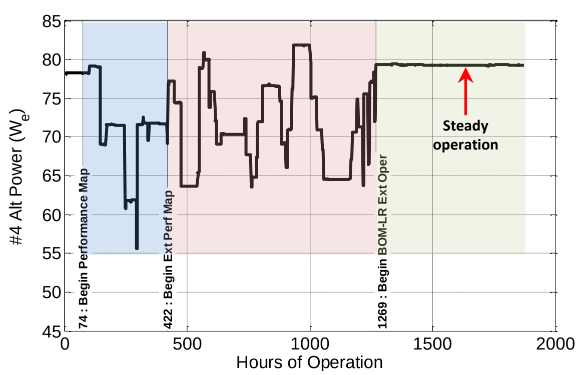

Figure 1. ASC-E3 #4 performance data.

During the first 1,270 hours, performance mapping and extended performance mapping were completed, requiring many changes in setpoint and resulting power output which explains the variability in data. The independent performance measurement at GRC showed that ASC-E3 #4 met the performance specification and matched Sunpower power output results within 3%. After 1,270 hours, the convertor has been on extended operation at the BOM LR condition. Only minor variations in performance due to environmental changes have been observed, which is expected. The convertor has otherwise operated flawlessly. Future plans for ASC-E3 #4 include acceptance level vibration testing followed by extended operation with a minimum of 500 hours of operation at each of the BOM and EOM reference test conditions.

ASC-E3 #3 was delivered to GRC in September 2013 and accepted with known issues from its production history. For this reason #3 performance data will not be included in the probabilistic reliability analysis, eventhough the intent is still to accumulate several thousands of hours of operation. This convertor has accumulated over 825 hours of operation, and is currently undergoing performance mapping.

ASC-E3 3rd pair are currently in the process of production at Sunpower, while the 4th pair has just initiated production.

Conclusion: GRC has established facilities for extended operation of several ASC units for the purpose of demonstrating long term performance and to develop the life and reliability database. The operating convertors are from several generations of the ASC design representing a range of developmental history with an emphasis on the latest engineering units, the ASC-E3s. The E3s incorporate design improvements learned from operation of the earlier engineering units, and were built to flight drawings and quality practices. While extended operation of all convertors is useful, extended operation of the E3 units is especially beneficial for validation of reliability models since these units are most representative of a flight unit. The initial ASC-E3s received were production pathfinders initiated prior to ASC-F fligt unit production and they have met the performance requirements per specification and have displayed stable performance. Future plans are in place for testing of a flight-like generator that integrates a pair of ASC-E3s, and for testing of an ASC-E3 under flight acceptance vibration loads which will further demonstrate the robustness of the ASC design.

References: [1] Oriti, S.M. (2013). Performance Measurement of Advanced Stirling Convertors (ASC-E3). *AIAA-2013-3813*. [2] Oriti, S.M. (2012). Test Hardware Design for Flight-like Operation of Advanced Stirling Convertors (ASC-E3). *AIAA-2012-4254*.