



Advanced Stirling Convertor (ASC)—From Technology Development to Future Flight Product

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Abstract

The Advanced Stirling Convertor (ASC) is being developed by Sunpower, Inc. under contract to NASA's Glenn Research Center (GRC) with critical technology support tasks led by GRC. The ASC development, funded by NASA's Science Mission Directorate, started in 2003 as one of 10 competitively awarded contracts that were intended to address the power conversion needs of future Radioisotope Power Systems (RPS). The ASC technology has since evolved through progressive convertor builds and successful testing to demonstrate high conversion efficiency (38 percent), low mass (1.3 kg), hermetic sealing, launch vibration simulation, EMI characterization, and is undergoing extended operation. The GRC and Sunpower team recently delivered two ASC-E convertors to the Department of Energy (DOE) and Lockheed Martin Space Systems Company for integration onto the Advanced Stirling Radioisotope Generator Engineering Unit (ASRG EU) plus one spare. The design of the next build, called the ASC-E2, has recently been initiated and is based on the heritage ASC-E with design refinements to increase reliability margin and offer higher temperature operation and improve performance. The ASC enables RPS system specific power of about 7 to 8 W/kg. This paper provides a chronology of ASC development to date and summarizes technical achievements including advancements toward flight implementation of the technology on ASRG by as early as 2013.

Introduction

For NASA space applications where effective use of conventional photovoltaics is not possible such as for deep space applications or for extended surface applications on Mars or the Moon, Radioisotope Power Systems (RPS) are needed. NASA has successfully utilized RPS that convert the heat generated from the decay of radioisotope material into useful electrical power in the past, however, all previous flight RPS utilized thermoelectric power conversion. The latest of these was launched as part of the New Horizons spacecraft, NASA's Pluto-Kuiper Belt Mission which utilized a General Purpose Heat Source powered Radioisotope Thermoelectric Generator (GPHS-RTG). To address future mission power requirements including significantly higher efficiency and higher specific power compared to the GPHS-RTG, NASA released NASA Research Announcement (NRA) 02-OSS-01 entitled "Radioisotope Power Conversion Technology" (RPCT) soliciting proposals for development of next generation power conversion technology (NASA, 2002). The objective of the RPCT Project, managed by NASA Glenn Research Center (GRC), is to advance the development of power conversion technologies to provide higher efficiency to minimize the radioisotope fuel requirements and maximize specific power. Other general Advanced RPS goals include safety, long-life, reliability, scalability, multimission capability (vacuum and atmosphere), resistance to radiation (from the GPHS or potential mission environments), and minimal interference with the scientific payload. The emphasis of the RPCT NRA contracts is the development of the power conversion technology (converting heat to electric power). Integration of the power convertor into an RPS system, including GPHS modules, heat rejection, insulation, and structure

are the responsibility of the Department of Energy (DOE) and selected system integration contractors and was not within the scope of the original NASA RPCT project.

Phase I of the RPCT Project was initiated in the summer/fall of calendar year 2003 when ten NRA contracts were awarded (Wong, 2004). The selections included a broad range of conversion technologies including free-piston Stirling, turbo-Brayton, thermoelectrics, and thermophotovoltaics. In July/August 2004, an annual review was conducted of all ten Phase I RPCT NRA contracts with a review committee including personnel from NASA Headquarters, GRC, Jet Propulsion Laboratory (JPL), DOE, and Orbital Sciences Corporation. Results of the rigorous Phase I review identified Sunpower's Advanced Stirling Converter (ASC), as very highly ranked among the ten awarded contracts due to early hardware demonstrations of performance during Phase I and continued relevance to NASA's goals.

Advanced Stirling Converter Development

The ASC is being developed by an integrated team led by Sunpower, Inc. of Athens, Ohio and NASA GRC for integration onto the Advanced Stirling Radioisotope Generator (ASRG) being developed by DOE's system integration contractor Lockheed Martin Space Systems Company (Shaltens and Wong, 2007). Adoption of the free-piston ASC technology on the ASRG followed significant achievements made during Phase I and Phase II of Sunpower's RPCT NRA technology development effort. Objectives of converter efficiency >30 percent and low mass were quickly met early in Phase I with continued refinement and improvement in the technology in Phase II and Phase III (Wood, 2006). Early successes led to decisions by NASA to accelerate development by increasing technical support from GRC, procurement of additional hermetic units for life and reliability assessment, integration onto the ASRG generator, and re-planning Phase III of the ASC project. The ASC consists of the free-piston Stirling engine integrated with a linear alternator to produce electricity and is sized for the thermal output of a single General Purpose Heat Source (GPHS) module. To date, Sunpower has produced five generations of ASC-related hardware evolving the technology progressively with each build. Estimates for the latest ASC-E2 build, the design of which has recently begun, indicates power output of 84.5 W_{AC} with heat input from the GPHS to the ASC of 224 W_{thermal} indicating efficiency of 37.7 percent with a maximum heater head temperature of 850 °C, a reject temperature of 90 °C, a converter mass of 1.32 kg, a pressure of 3.65 MPa absolute, and an operating frequency of 102 Hz. The ASC-E2, shown in figure 1, is based on the heritage ASC-E converters that were completed in October 2007 and delivered by the GRC/Sunpower team to DOE and Lockheed Martin for integration on to the ASRG EU (Chan 2007). This paper provides a chronology of the development of the ASC, summarizes design features, highlights technical achievements, discusses status and plans, and describes the evolution from a technology development project to a possible flight product that could support a potential flight opportunity of the ASRG as early as 2013 (NASA, 2007).

A simplified layout of the ASC is shown in figure 2. The key technologies in the ASC that enable high efficiency and low mass are the hydrostatic gas bearings, a moving-magnet linear alternator, high-frequency operation, high-temperature hot end materials and fabrication processes, and high-temperature, high-porosity regenerators. The gas bearings for the ASC reside within the piston and are charged from the engine working space via a check valve within the piston. The displacer is sprung by means of a single planar spring located outboard from the working space and alternator as seen in figure 2. The use of gas bearings and the outboard displacer spring allows for a very compact working space of the machine which in turn helps lead toward high converter efficiency. With this arrangement the heater head of the machine can be made rather small which helps reduce conduction losses which are significant in small machines. Additionally the compact working space allows for high operating frequency which allows for higher specific power. Important is the high efficiency and low mass Sunpower linear alternator which is of the single-window moving magnet type. This alternator makes full use of the copper winding as the winding is located entirely within the reversing magnetic flux. The laminations also have a zero-mean magnetic flux, so that the lamination material is used efficiently.

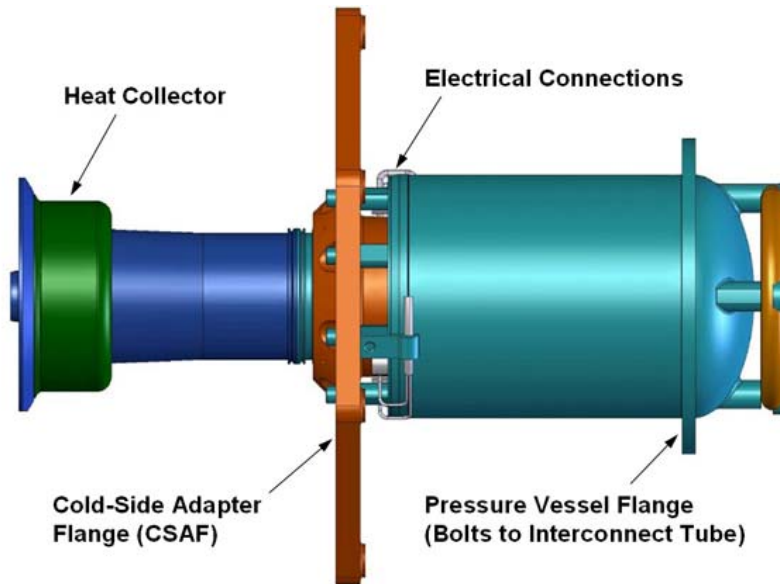


Figure 1.—Sunpower Advanced Stirling Converter (ASC-E2) with External Interfaces.

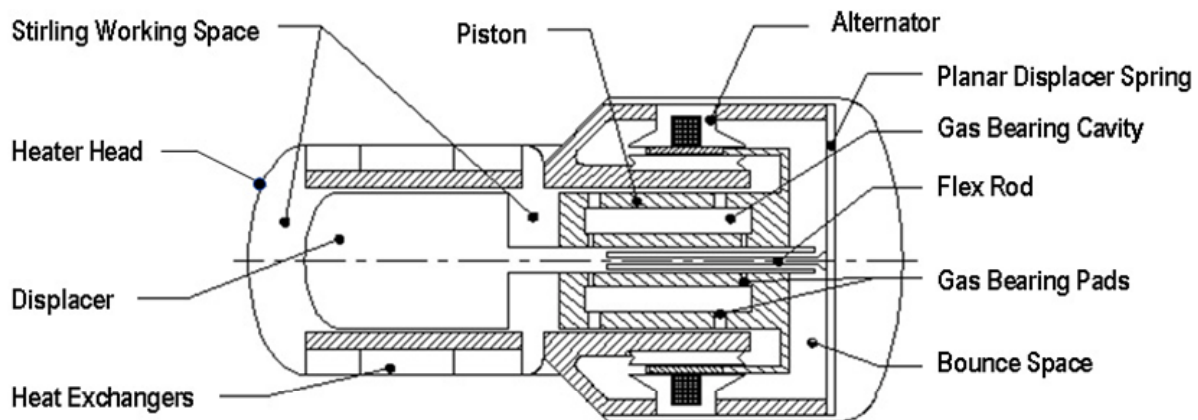


Figure 2.—Simplified Layout of the Sunpower Stirling Engine with Linear Alternator.

The ASC is similar in design configuration and size to thousands of commercial terrestrial cryocoolers in the field that were manufactured by Sunpower or Sunpower licensees lending confidence to the reliability of the ASC. Further, Sunpower cryocooler technology has flown, demonstrating reliable operation in space applications with one in particular that continues service aboard NASA's RHESSI satellite which was launched on February 5, 2002 (Wood, 2006).

Phase I—Early Technology Demonstration

During Phase I (2003/2004), Sunpower demonstrated the feasibility of the ASC by building an early prototype called the Frequency Test Bed (FTB) Stirling convertor which was designed, fabricated, and was made operational within the first five months of Phase I, one month ahead of schedule, to allow operational and advanced component investigations. The FTB which was quickly designed and built of common materials such as a stainless steel heater head surpassed project efficiency goals having demonstrated 36 percent conversion efficiency (AC power out/heat in) at 650 °C hot end temperature and 30 °C reject temperature (temperature ratio of 3.0) with output power greater than 80 We. The FTB retired a risk to the project by demonstrating that high efficiency and high specific power were achievable



Figure 3.—FTB Stirling Converter established performance potential and guided ASC design.

and that conduction losses and seal losses in small machines operating at high frequency can be minimized. Testing of the FTB (fig. 3) provided guidance on the later design of the high frequency ASC. In addition to the FTB hardware demonstration during Phase I, Sunpower led a team consisting of Pratt and Whitney Rocketdyne (PWR), Cleveland State University (CSU), University of Minnesota (UMn), and several Stirling consultants to complete the design of the ASC-1 factoring in results from various hardware and analytical investigations. The ASC is intended to maximize performance by operating at higher temperatures up to 850 °C compared to other Stirling devices being considered for RPS which operate at 650 °C hot end temperature limited by the use of IN718. As a part of ongoing Stirling technology development effort at NASA GRC separate from the Sunpower ASC effort, in consideration of the very long life requirements of the RPS application (17 years) various high temperature candidate materials and specifications for Stirling heater heads were being evaluated and recommended (Bowman, 2003). The Sunpower ASC team considered these candidate materials and results of ongoing creep testing of materials at GRC as well as other candidate materials and adopted the recommended material of MarM-247 for the heater head based on creep strength, alloy maturity, and fabrication/joining requirements. Also, Udimet 720 was selected for the displacer dome assembly.

Supporting Sunpower on the production of the high temperature components, PWR provided high temperature materials and joining expertise by selecting appropriate casting parameters for large grain MarM-247 ingots, conducting additional creep tests on this material, provided recommendations on the fabrication and processing steps to produce and join the high temperature components, and produced and evaluated initial fabrication and coupon joining trials. To refine the ASC design, Sunpower supported by the consultants performed thermodynamic trades and evaluated loss mechanisms in order to optimize the ASC. Studies included a displacer loss investigation which included hardware testing performed by Sunpower and CFD modeling by CSU which showed that the number of displacer baffles could be reduced. The impact of this work manifests as a cost savings (fewer parts), reduced fabrication risk to the hardware (simplifying manufacturing), and higher reliability design (lower part count) with no impact on performance. Regenerator perimeter loss and jetting effect studies were also carried out both analytically and through testing by UMn using a large-scale regenerator mock-up test rig. Finally, a reliability assessment effort has been ongoing since project inception and continues now to evaluate any potential life-time performance risks and to guide other test and analytical activities.

By the conclusion of Phase I, the ASC team successfully demonstrated the performance potential of the ASC configuration with the FTB and completed the initial design of the ASC-1 to be built during Phase II with high confidence that the performance objectives could be improved upon.

Phase II—ASC-1 Production and High Temperature Performance Verification

The objective of Phase II (2004/2005) was the production and testing of four ASC-1 convertors utilizing high temperature materials and joining techniques and demonstrating performance at 850 °C hot end temperature. The ASC-1 is a developmental unit that has bolted flange connections of the structural components rather than the hermetic joints required for a flight unit. For the 17 year life requirement (notional 14 year mission plus 3 year fueled storage), creep strength of the thin walled heater head at high temperature is vital. Due to the fabrication and processing complexity of the heater head and the long lead time of the component, the four ASC-1 convertors were sequenced into two builds to minimize development risk and alleviate schedule pressure. The first pair ASC-1 #1 and #2 would demonstrate operation and processing with the exception that it would use an all-MarM-247 heater head shell, and the second pair ASC-1 #3 and #4 would demonstrate the inertia weld joint between the MarM-247 heater head shell and an IN718 mating component. Because MarM-247 can not be fusion welded, in a hermetic configuration the MarM-247 head must be joined by other means to a transition material that can then be fusion welded to the rest of the convertor. For ASC-1 (and later for ASC-1HS), inertia welding was adopted for joining MarM-247 to the IN718 weld flange, and demonstrated successfully.

The earlier GRC characterization of MarM-247 was all conducted on finer grain MarM-247 compared to the larger grain material used on the initial ASC builds. To minimize project risk, in parallel to the ASC effort, GRC continued to investigate other MarM-247 casting techniques and parameters that result in much finer grain size. GRC continues to characterize MarM-247 in order to select the appropriate material parameters most suitable for the unique ASC application including creep testing of fine, medium, and large grain MarM-247. Additionally, GRC developed a braze option for joining the MarM-247 shell to the IN718 weld flange as an alternative solution for that joint.

For high temperature operation, not only does the heater head require high temperature capable material, so does the displacer, regenerator, and hot cylinder. Thin Udimet 720 displacer dome and baffle fabrication, processing and joining were demonstrated during Phase II as was the incorporation of the Udimet 720 hot cylinder. Based on prior work, NASA GRC recommended the oxidation-resistant high-temperature regenerator material, and later developed the processing of the high porosity regenerator sections and provided them to Sunpower for inclusion in the convertor builds. The performance and reliability assessment tasks started in Phase I also continued during Phase II. In particular, the Hot Alternator Test Rig (HATR) was built specifically to characterize ASC linear alternator performance at elevated temperatures and then to destructively test the alternator to identify temperature induced failure mechanisms and temperature limits of the design.

During Phase II, four ASC-1 convertors were completed (fig. 4). The first ASC-1 was completed on time and initial operation met the project milestone on September 15, 2005. Less than a month later, the ASC-1 demonstrated conversion efficiency of 38 percent (AC power out/heat in) with 88 W_{AC} power output at 850 °C hot-end and 90 °C cold-end temperatures. Later, two of these units were operated in a dynamically opposed low vibration configuration. During Phase II, it was shown that the ASC design is capable of higher power output if unconstrained to the thermal input limit of a GPHS module. During testing of the ASC-1, a maximum power output of 114 W_{AC} was achieved (Wood, 2006). A launch vibration test that was originally part of Phase II was re-planned due to cost and hardware availability considerations for Phase III. In April 2007, ASC-1 #4 completed a series of simulated launch vibration levels at PWR. While the ASC was operational producing power, testing was performed in both the axial and lateral directions. Testing was completed at workmanship level (6.8 grms random) for 1 min, flight level (8.7 grms random) for 1 min, and qualification level (12.3 grms random) for 3 min. In addition, ASC-1 #4 was operated at qualification 3 dB (17.5 grms random) for 1 min. After successful launch simulation testing, ASC-1 #4 and a matching convertor, ASC-1 #3, were delivered to GRC for continuous operation in May 2007.



Figure 4.—Four ASC-1 developmental converters capable of operation at 850 °C hot end temperature.

Phase III—Hermetic Convertors, ASRG System Integration, and Transition to Flight

Achievements during Phase I and Phase II including successful performance demonstration of the FTB and ASC-1 and on-time completion of the hardware, as well as continued relevance of the ASC technology to NASA's future needs, resulted in re-planning of the Sunpower ASC project based on the following major changes:

1. *Integrated GRC Technical Support*—In the Fall of 2005, towards the end of Phase II, NASA Headquarters directed NASA GRC to shift in-house technology support from the previous Stirling Radioisotope Generator (SRG110) project to the ASC. Thus resources and expertise at GRC were made available to complement and accelerate ASC development.
2. *Additional Hermetic Convertors for Extended Operation*—Recognizing the need for more convertors to expand the operational database, GRC ordered additional hermetic ASC's with the direction to freeze the design of the ASC-1 and implement processing and hermetic sealing of the units. These units would be used to identify and resolve developmental issues and would be delivered to GRC for continuous extended operation in the Stirling Research Laboratory.
3. *ASC-E Adopted by DOE and Lockheed Martin for ASRG*—Due to the high efficiency and low mass of the ASC, in the Spring of 2006, DOE and Lockheed Martin initiated plans to substitute the ASC convertors into the SRG110 generator design increasing the system specific power from 3.5 W/kg to about 7 W/kg for the newly named Advanced Stirling Radioisotope Generator (ASRG). NASA and DOE entered an agreement under which GRC and Sunpower would deliver to DOE and Lockheed Martin two ASC-E convertors plus one spare for integration on to the ASRG Engineering Unit (EU). After Lockheed Martin completes generator level testing, the ASRG EU will be delivered to NASA GRC for extended testing in 2008.
4. *ASC-E2 - Preparing for Flight Implementation*—In the Fall of 2007, NASA announced the Discovery and Scout Mission Capabilities Expansion Program (NASA, 2007), seeking studies on mission concepts that are enabled by up to one pair of ASRGs with potential launch as early as 2013. To support this potential timetable, the ASC project has been re-planned to include the ASC-E2 build which is based on the ASC-E design while implementing higher temperature materials to increase reliability margin and offer higher temperature operation and increase performance. The emphasis of the ASC-E2 build would be to increase the design rigor and Quality system program to prepare Sunpower as an eventual supplier of hardware for a flight nuclear system. The ASC-E2 convertors

will be built in 2008–2009 for delivery to NASA GRC for extended testing to help develop the life and reliability database for operation up to 850 °C.

Integrated GRC Technical Support

NASA has been developing Stirling technology for various applications for decades and expertise resident at GRC had previously been supporting the development of the SRG110 (Schreiber, 2007). In the Fall of 2005, GRC was directed to shift in-house technology support to accelerate the development of the ASC. Beyond management of the ASC project, GRC's role was expanded to include convertor, component, and materials testing and analysis to address life and reliability, reduce risk, and prepare for RPS flight development. Specifically, GRC tasks include:

- (1) Reliability and quality assurance
- (2) In-house convertor and component testing
- (3) High-temperature materials and structures
- (4) Electromagnetic interference and electromagnetic compatibility
- (5) Computational fluid dynamics modeling of gas bearings
- (6) Organic materials development and characterization
- (7) Magnet aging and characterization
- (8) Support of the Lockheed Martin controller development

The appreciable technology development tasks being performed at GRC to support ASC is discussed in greater detail by Schreiber and Thieme, 2008. Several highlights include the continued uniaxial creep testing of MarM-247 thin specimens to build a database on which heater head life and reliability predictions can be based, as well as the multi-axial benchmark creep testing of representative ASC heater heads (Krause, 2007). Organic materials assessment evaluates adhesive bonding integrity, outgassing characteristics, thermal stability, durability and reliability of epoxies and coatings for the ASRG application and provides guidance on processing and cure conditions to maximize material performance (Shin, 2008). Gas bearings are being evaluated to determine stiffness and provide guidance on potential optimization using modeling tools described in Dyson, 2005. Reliability assessment of the ASC is also performed through deterministic and probabilistic analysis of the heater head as well as general support of the ASRG Reliability Working Group (Ha, 2008). Convertor in-house testing in GRC's Stirling Research Laboratory (SRL) consists of six in air test rigs plus a thermal vacuum rig, each of which supports testing of a pair of convertors in dual opposed configuration. As of February 4, 2008, Sunpower has delivered eight ASC convertors to GRC for extended testing and these convertors have accumulated a total of 24,914 hr with 7,580 hr on each ASC-0 unit in thermal vacuum. Total accumulated hours on all convertors at GRC's SRL total 159,422 hr with the leading pair of TDC convertors having 34,569 hr each. Including hours accumulated at Sunpower, total hours on all ASC convertors total 28,136.

Additional Hermetic ASC Convertors for Extended Operation

GRC ordered additional hermetically sealed convertors based on the ASC-1 design intended for extended operation in GRC's Stirling Research Laboratory. The goal of having these units is to provide life and reliability data and conduct performance evaluation of the ASC technology. Past experience has identified the criticality of hermetic units for long duration testing, eliminating the possibility of trace contaminants or minute pressure changes during the course of extended operation. The hermetic units include two lower temperature convertors using IN718 heater heads limited to 650 °C operation named ASC-0 (indicating a less advanced lower temperature capability), which could be delivered in a shorter timeframe. Later, two additional ASC-0 units were ordered. The two higher temperature convertors using MarM-247 heater heads allowing 850 °C operation are named ASC-1HS (signifying that they are based on the ASC-1, but hermetically sealed). These early hermetically sealed units would be used to identify

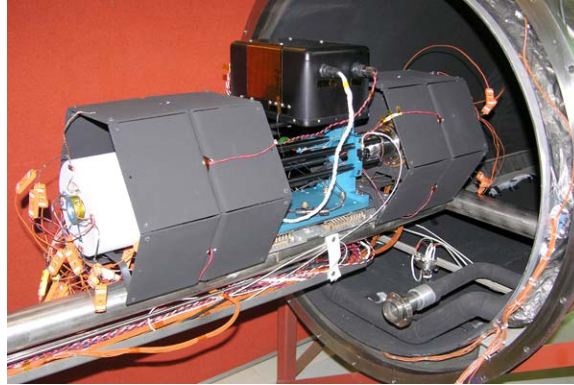


Figure 5.—ASC-0 #1 and #2 installed in GRC's Thermal Vacuum Facility in the Stirling Research Laboratory

any developmental issues and to develop processing techniques for the subsequent hermetically sealed convertors. Improvements in quality practices and critical process documentation were initiated starting with the initial ASC-0 build. Developmental issues identified as part of these additional hermetic ASC convertors are detailed in Wood 2007.

A pair of ASC-0s was completed and delivered to GRC in December 2006. Initial testing was completed in air for over 600 hr, after which the convertors were installed and are operational in a thermal-vacuum facility in GRC's Stirling Research Laboratory (fig. 5). In the thermal vacuum setup, the ASC-0s are heated electrically and cooled by attachment to radiators that reject heat to the facility cold-walls. The second pair of ASC-0s delivered to GRC in July 2007 are continuing extended operation in air. The ASC-1HS pair was delivered in November 2007 and is being prepared for initial operation in air, and will be followed by installation in the thermal-vacuum facility, replacing the initial ASC-0 pair. The ASC-1HS hardware also has undergone precise head profile measurements which will be checked periodically during future disassemblies in order to quantify creep of operational heads for verification of analytical creep analysis predictions. GRC in-house testing of the ASC convertors and a description of the facilities and autonomous test setups that allow continuous safe operation are described in Oriti, 2007; Schreiber, 2008.

ASC-E Adopted by DOE and Lockheed Martin for the ASRG

After successfully demonstrating the performance of the ASC technology in Phase I and Phase II, Lockheed Martin Space Systems Company, DOE's system integration contractor for SRG110, initiated the substitution of the ASC technology into the generator design renaming it the ASRG EU. The ASRG EU, described in Chan 2007, is not an optimized design in that it utilizes existing long lead and high value parts from the SRG110. Still, it was anticipated that the high efficiency and low mass of the ASC would increase the specific power of the generator from 3.5 W/kg for SRG110 to about 7 W/kg for a flight ASRG configured similarly to the EU. Further, the small size of the ASC allows about 25 percent reduction in the ASRG housing length. It is estimated that greater than 8 W/kg specific power is possible in an optimized ASRG design (Chan, 2007).

The ASRG EU shown in figure 6, utilizes two ASC-E (for ASC-Engineering Unit) convertors that are electrically heated. Direction was given that for the initial ASRG EU, lower temperature IN718 materials would be used due to schedule and material maturity considerations. For the previous ASC builds, due to the scope of the RPCT project, minimal consideration of generator system design interfaces and integration requirements were included in the design. Earlier builds were all designed as developmental laboratory units. The adoption of the ASC on to the ASRG EU allowed an opportunity to significantly advance the technology by inclusion of integration interfaces and system requirements flowed-down from the generator design.

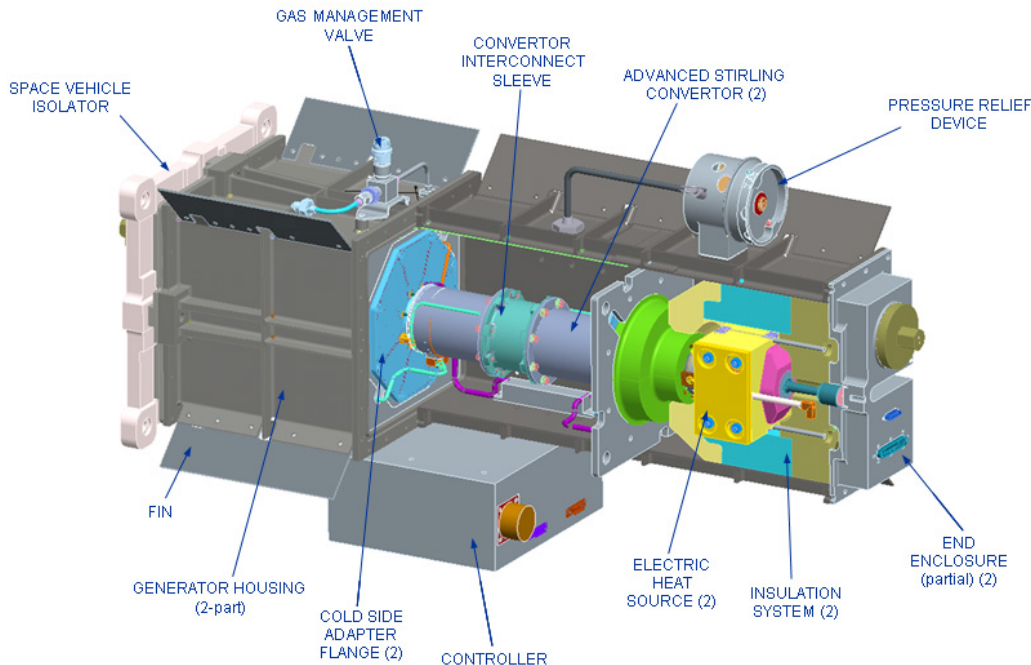


Figure 6.—DOE/Lockheed Martin's Advanced Stirling Radioisotope Generator Engineering Unit (ASRG EU).

Initial trade studies were performed by GRC, Sunpower, and Lockheed Martin to assess features and design modifications that would be required to evolve the ASC from the previous technology development design to one suitable for integration onto the ASRG EU. The ASC-E design modifications include a heat collector and a Cold-Side Adapter Flange (both thermal and structural interfaces to the ASRG), an additional structural interface on the pressure vessel to allow mating of a pair of convertors, an internal piston position sensor, and feed through electrical interfaces for power and the piston position sensor. Sunpower and GRC completed the ASC-E design review in November 2006, and fabrication of two convertors plus a spare was initiated. Subsequently, Lockheed Martin held the ASRG EU final design review in February 2007.

For the ASRG EU, the development of the controller is the responsibility of Lockheed Martin. GRC and Sunpower provided several Stirling convertors for controller developmental testing at Lockheed Martin. Initially, a pair of FTB convertors was provided, and later a pair of ASC-1 convertors modified with internal piston position sensors similar to the ASC-E configuration was delivered. Sunpower and GRC also participated in integration testing of the Lockheed Martin controller with an ASC-E, early in the production of the ASC-E convertors prior to hermetic sealing.

In addition to design modifications, the quality practices involved in producing the ASC-E units were required to be more rigorous compared to the previous developmental builds. Configuration management, establishment of an ASC-E Engineering Review Board to approve design modifications and non-conformances, and more detailed process documentation, test plans, and test procedures were all instituted as part of the ASC-E build. The ASC-E was assembled and operational by July 2007 providing full power during initial testing “right out of the box.” Subsequent processing included burn-in tests, welding of the external structure, vacuum bake-out, and fill-and-purge cycling of the helium working gas.

Given the new processes and documentation requirements of the ASC-E, the eleven month build schedule between the ASC-E design review and delivery in October 2007 was highly aggressive. Accomplishment of on-time delivery was made possible by a dedicated and truly integrated team consisting of personnel from GRC, Sunpower, and Lockheed Martin. From ASC-E project inception continuing after hardware delivery, the team collaborated on all aspects of the project including requirements definition, trade study closure, design completion, process development, component

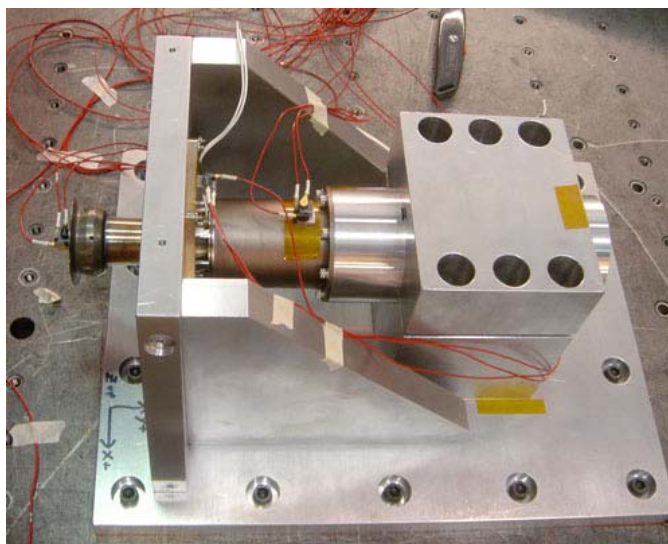


Figure 7.—ASC-E being installed at GRC's SDL preparing for Workmanship Vibration Testing up to 6.8 grms.

production, subassembly testing, convertor processing and assembly, convertor testing, delivery, documentation, and review. While Sunpower had the responsibility of producing the ASC-Es, both GRC and Lockheed Martin also contributed to the success of the hardware. Lockheed Martin provided the design and hardware for the nickel heat collectors and the copper-based Cold-Side Adapter Flanges (CSAF) and performed external feedthrough soldering and potting. GRC provided the oxidation resistant high temperature regenerators, performed soldering and wire routing related to internal electrical feedthroughs, assisted in various braze joint development, as well as many other aspects of coordination, inspection, and testing. Further, GRC conducted workmanship vibration testing in the Structural Dynamics Laboratory (SDL) on each completed and hermetically sealed ASC-E convertor to 6.8 grms in all three axes (fig. 7).

After completion of all processing and workmanship vibration testing, the three ASC-Es underwent final performance verification testing at Sunpower before delivery to Lockheed Martin. The first pair of ASC-E convertors were delivered on schedule by GRC and Sunpower to DOE and Lockheed Martin on October 4, 2007. The spare unit was also delivered on-time on October 29. The convertors successfully passed acceptance testing at Lockheed Martin and are now being integrated into the ASRG EU for generator level testing and characterization.

The initial ASC-E pair shown in figure 8 each produced about $78 W_{AC}$ exceeding the $75 W_{AC}$ requirement at reference operating conditions of $640^{\circ}C$ hot-end temperature and $60^{\circ}C$ rejection temperature with 224 W heat input. The 35 percent power conversion efficiency of the ASC-E enables the ASRG to have a specific power of about 7 We/kg. Further, the high efficiency represents a factor of 4 reduction in the radioisotope fuel requirement compared with lower efficiency thermoelectric based radioisotope power systems.

ASC-E2—Preparing for Flight Implementation

On September 22, 2007, NASA's Science Mission Directorate released an NRA for Discovery and Scout Mission Capabilities Expansion Program (DSMCE) (NASA, 2007) seeking proposals for mission concepts that are enabled by up to two ASRGs with potential launch as early as 2013. To support this timetable, the ASC project has been re-planned to further accelerate development towards flight including the start of the ASC-E2 build (fig. 9). The ASC-E2 is based on the heritage ASC-E design delivered to Lockheed Martin for ASRG EU integration with several key technology and programmatic refinements.

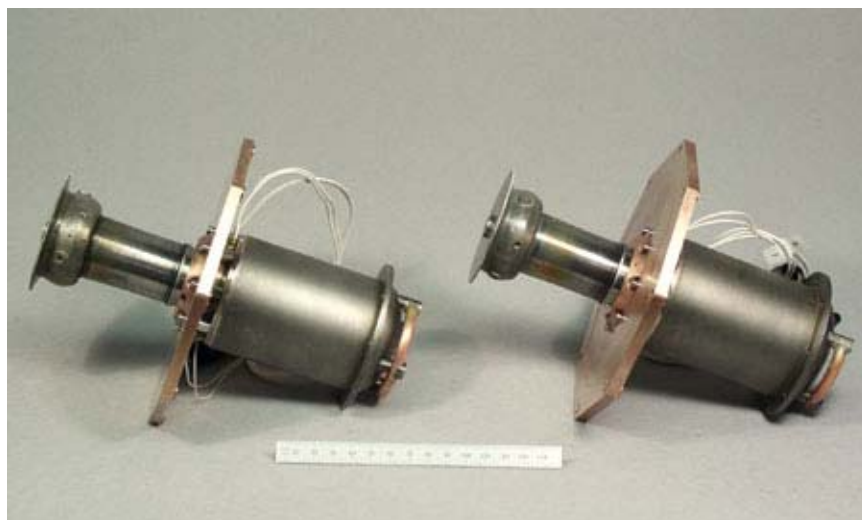


Figure 8.—Pair of completed ASC-E convertors delivered to Lockheed Martin for integration on to ASRG EU.

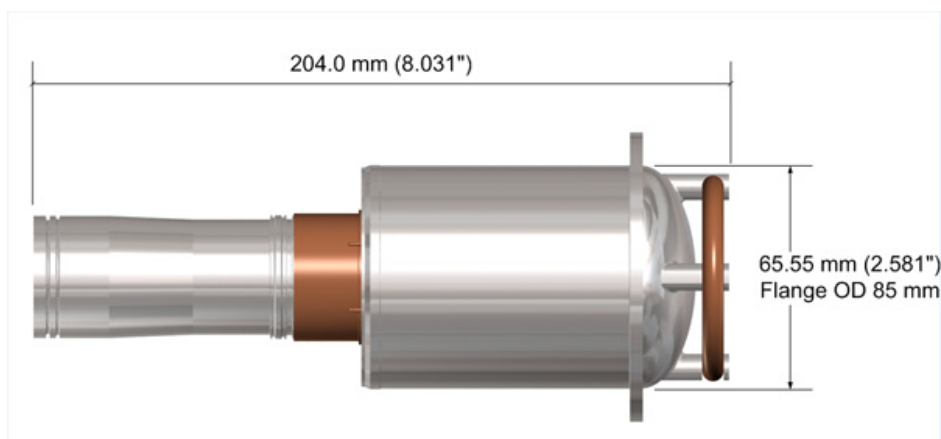


Figure 9.—ASC-E2 Preliminary Design without Heat Collector and Cold-Side Adapter Flange (CSAF) Interfaces.

The ASC-E2 will utilize MarM-247 and Udimet 720 materials rather than the IN718 used on ASC-E to increase reliability margin and offer higher temperature operation and increase performance. Thus the ASC-E2 will revert to the original high temperature materials that were implemented on the earlier ASC-1 and ASC-1HS convertors, but with refinement in design and processing. The ASC-E2 will include a heat collector interface to the heat source that is capable of higher temperature operation and a more robust CSAF bond joint for heat rejection. Also, an emphasis of the ASC-E2 build is to increase the design rigor and Quality system program to prepare Sunpower as an eventual hardware supplier for flight nuclear systems. The ASC-E2 build was kicked-off on November 7–8, 2007, shortly after delivery of the third ASC-E.

The ASC-E2 convertors are intended for high temperature continuous extended operation. Unlike the ASC-E hardware, the ASC-E2s are not intended for integration into an ASRG. Nevertheless, integration interfaces and current ASRG requirements will be adhered to (with updates) so that the ASC-E2 design, processing, testing, documentation and quality methods maintain relevance to the eventual ASRG flight application. Transitioning the ASC for flight would not simply be refinement of the hardware, but of the practices and methods used as part of producing the product as well. As part of this transition, for the ASC-E2 build, Sunpower is currently adding to the infrastructure to support ASC development including

installation of a dedicated NASA ASC facility, refinement in design practices, upgrade in design software, addition of dedicated equipment for welding, and increased inspection capability.

Conclusion

In consideration of the origins of the ASC project from the start of the NRA technology development contract in 2003, to the potential flight opportunity in 2013, and the current status of the project in 2008, the ASC technology is at the midpoint both in terms of time as well as in terms of technology transition. The earlier convertors (FTB, ASC-1, ASC-0, ASC-1HS) were developmental units, each of which progressively advanced the technology through design refinements, improved processing methods, and demonstration of feasibility, temperature capability, and break-through performance. The just completed ASC-E and current ASC-E2 convertors, meanwhile, are part of transitioning the technology out of the development stage and into the eventual flight application and production stage. While some development is still needed and many technical challenges await, the current outlook is excellent for the ASC to exactly fulfill the objectives of the RPCT project, which is to provide NASA with a power conversion technology that enables a reliable high efficiency, high specific power RPS. Integrated into the ASRG, the Advanced Stirling Convertor could enable NASA missions as early as 2013 while minimizing the fuel requirements, and maximizing the specific power.

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14. ABSTRACT The Advanced Stirling Convertor (ASC) is being developed by Sunpower Inc. under contract to NASA's Glenn Research Center (GRC) with critical technology support tasks led by GRC. The ASC development, funded by NASA's Science Mission Directorate, started in 2003 as one of 10 competitively awarded contracts that were intended to address the power conversion needs of future Radioisotope Power Systems (RPS). The ASC technology has since evolved through progressive convertor builds and successful testing to demonstrate high conversion efficiency (38 percent), low mass (1.3 kg), hermetic sealing, launch vibration simulation, EMI characterization, and is undergoing extended operation. The GRC and Sunpower team recently delivered two ASC-E convertors to the Department of Energy (DOE) and Lockheed Martin Space Systems Company for integration onto the Advanced Stirling Radioisotope Generator Engineering Unit (ASRG EU) plus one spare. The design of the next build, called the ASC-E2, has recently been initiated and is based on the heritage ASC-E with design refinements to increase reliability margin and offer higher temperature operation and improve performance. The ASC enables RPS system specific power of about 7 to 8 W/kg. This paper provides a chronology of ASC development to date and summarizes technical achievements including advancements toward flight implementation of the technology on ASRG by as early as 2013.					
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