Advanced Stirling Technology Development at NASA Glenn Research Center

Richard K. Shaltens Wayne A. Wong National Aeronautics and Space Administration Glenn Research Center at Lewis Field 21000 Brookpark Road Cleveland, OH 44135

Abstract - NASA's Glenn Research Center (GRC) has been developing advanced energy conversion technologies for use with both Radioisotope Power Systems (RPS) and Fissions Surface Power Systems (FSPS) for many decades[1, 2, 3]. Under NASA's Science Mission Directorate, Planetary Science Theme, Technology Program, GRC is developing the next generation of Advanced Stirling Convertors (ASC) for use in the DOE/Lockheed Martin Advanced Stirling Radioisotope Generator (ASRG) [4, 5.] The next generation power conversion technologies require high efficiency and high specific power (We/kg) to meet future mission requirements using less of the Department of Energy (DOE's) Plutonium fueled General Purpose Heat Source (GPHS) Modules and reducing the system mass. Important goals include long-life (> 14 years) reliability, and scalability so that these systems can be considered for a variety of future applications and missions including outerplanetary missions and continual operation on the surface of Mars. This paper provides an update of the history and status of the development of the Advanced Stirling Convertor (ASC) being developed for GRC by Sunpower Inc., Athens, OH.

I. BACKGROUND

In 2002, NASA released the NASA Research Announcement (NRA) 02-OSS-01 entitled "Radioisotope Power Conversion Technology" (RPCT) requesting proposals for the development of the next generation power conversion technology [6]. The objective of the RPCT Project is to advance the development of power conversion technologies to provide higher efficiencies and specific power than the state-ofthe-practice GPHS RTG. Other goals include safety, long life (> 14 years with well understood degradation), reliability, scalability, multimission capability (in atmosphere or vacuum of space), resistance to radiation (from the GPHS or potential mission environments) and minimal interference with the spacecraft payload. The focus of the NRA contracts is to develop the power conversion technology, converting heat to electric power.

The RPCT Project was initiated in the summer/fall of 2003 when ten contracts were awarded by NASA GRC. The awards were for five "Development" contracts using more mature technology between Technology Readiness Level (TRL) 3-5 and five "Research" contracts using less mature technology (TRL 1 to 3). The development contracts selected included a broad range of conversion technologies including the free- piston Stirling convertor [7], the turbo-Brayton [8], thermoelectric (TE) [9], and thermophotovoltaics (TPV) [10], 2005 and [11]. The NRA contracts were originally divided into three one-year phases, with options to continue into the next phase based on government review of status. Annual reviews were conducted for the ten NRA RPCT contracts at the end of both Phase I and Phase II [5]. Currently two Phase III "Development" contracts continue for the ASC free-piston Stirling convertor with Sunpower, Athens, Ohio and the Thermophotovoltaic convertor with Creare, Hanover, NH and one "Research" contract for the micro-fabricated Stirling regenerator with Cleveland State University, Cleveland, Ohio. The fourth contract that continued into Phase III was with Massachusetts Institute of Technology, Cambridge, MA for Nano-SiGe thermoelectrics "Research" that has been concluded. The following will provide the status of the development for the Advanced Stirling Convertor with Sunpower, Inc.

II. ADVANCED STIRLING CONVERTOR DEVELOPMENT

A. Phase I

Sunpower, Inc. (Athens, OH) is leading the team consisting of United Technologies Companies -Rocketdyne (UTC-R) (previously know as Pratt & Whitney Rocketdye), University of Minnesota (UMn) and several consultants to demonstrate the technology of an Advanced Stirling Convertor (ASC). The ASC consists of the freepiston Stirling engine integrated with a linear alternator to produce electricity. 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 (> 100 Hz), use of high temperature heater head materials and fabrication processes, and high temperature high porosity regenerators. The charge pressure of the ASC is 3.5 MPa and the frequency is about 105 Hz. The original goals of the ASC were to achieve efficiency of greater than 30% (AC power out/heat in), with a design output power of greater than 80 We AC making feasible a projected RPS specific power of about 8 We/kg [12]. As identified below, the ASC performance goals have now been met.

The ASC being developed uses similar technologies to Sunpower's commercial cyrocoolers. A Sunpower cryocooler is currently being used on NASA's RHESSI satellite was was launched in February 2002.

During Phase I, Sunpower designed and build a Frequency Test Bed (FTB) Stirling convertor to investigate the advanced technologies in their proposal. Use of the FTB would allow evaluation of the advanced concepts and provide guidance on the design for the ASC. The FTB was made operational within the first five months of Phase I. The performance surpassed the goals (> 30 per cent) of the project having demonstrated 36 per cent conversion efficiency (AC power out/heat in) at an operating temperature of 650 °C heater head and 30 °C rejection temperature with a power output of 80 We (AC). Operation of the FTB, shown in Fig. 1, at these temperatures represent a temperature ratio of 3, which is representative of the Sunpower ASC design which would operate at the higher temperatures of 850 °C (heater head) and 90 °C (rejection).



Fig. 1. The Sunpower Frequency Test Bed Convertor (FTB)

The ASC-1s, shown in Fig. 2, was designed during Phase I, with four non-hermetically sealed units planned for fabrication during Phase II. The ASC is deigned to operate at 850 °C heater head temperature using available materials technology with MarM-247. Prior to the selection of the MarM-247, a variety of candidate high temperature materials were considered by the Sunpower team including materials that were evaluated and recommended by NASA [13, 14]. Creep testing of the MarM-247 head material continues with thin test samples that replicate the heater head wall thickness. Over 30 creep tests have been completed to date, characterizing a range of MarM-247 casting variables and specimen thickness. The heater head is designed with a conservative approach including estimates based on these data. While use of IN718 has been demonstrated to show sufficient life (17 yrs) at 640 °C when used in the ASC, analysis of the MarM-247 (0.999 probability of survival) shows that the design life of the heater head operating at 850 °C is in excess of 70 yrs. Use of MarM-247 greatly enhances the reliability by providing significant margin in the ASC design.



Fig. 2. Four Non-Hermetic Advanced Stirling Convertors (ASC -1)

For the RPS 14 year life requirement, the high temperature requirements of the ASC, creep strength of the thin walled heater head pressure vessel is paramount. After reviewing the creep data provided by NASA, the ASC team also conducted thin sample creep testing of MarM-247. Analysis indicated the projected 1 per cent creep over the heater head over 14 years had no impact on the ASC performance. The ASC project team developed a variety of coupon, joining and processing tests that were carried out during Phase I and II to develop the proper processing techniques for the heater head.

In addition to the development of the convertor hardware and materials development work, significant effort during Phase I also involved reliability studies, component testing, advanced component investigations, and thermodynamic loss investigations.

B. Phase II

During Phase II Sunpower completed the design and fabrication of four non-hermetic ASC-1 convertors which have the capability of operating with a heater head temperature at 850 °C. The purpose of the multiple ASC-1s is to gain initial operating experience with nonhermetic laboratory developmental convertors using the higher temperature materials operating in single and dual-opposed configuration. Testing and operation of these units would further guide the design of the hermetic ASC-2 convertors to be built in Phase III. Two of the ASC-1s have all Mar-M heater heads and two have an inertia welded MarM-247 heater head.

Besides the MarM-247 heater head, to allow the ASC-1 to operate at the higher operating temperatures, high temperature displacers, regenerators, and hot cylinders are also required. During Phase II, the Udimet 720 displacer dome and baffle processing and joining were demonstrated 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 regenerator sections and provided them for inclusion in the convertor build.

Testing during Phase II demonstrated the ASC-1 conversion efficiency of 38% (AC out/ heat input) with 88 We AC power output at 850 °C

hot end and 90 °C cold end temperatures. It should be noted that the ASC-1 design is capable of higher power output if unconstrained to the thermal input limit of a GPHS. During testing, the ASC-1 demonstrated a maximum power output of 114 We AC.

As part of the reliability assessment, during Phase II, a Hot Alternator Test Rig (HATR) was developed to characterize the ASC linear alternator performance at elevated temperatures and then to destructively test the alternator to identify temperature induced failure mechanisms.

C. Phase III

Based on the successful performance demonstrations and continued relevance of the ASC to NASA's future needs, the current Phase III of the project has been modified in three major ways:

- 1. NASA GRC was directed by NASA Headquarters to focus in-house technology efforts to support the development of the ASC
- 2. Four additional accelerated hermetic convertors were ordered based on the ASC-1 that are intended for 24/7 extended operation at GRC to identify and resolve development issues and to provide life and reliability data
- 3. The GRC/Sunpower contract was modified to include three hermetic ASC-E convertors to support the development of the DOE/Lockheed Martin Advanced Stirling Radioisotope Generator (ASRG).

To allow for this additional work and also to continue developmental efforts prior to commitment to a final design, the Sunpower contract was extended and the fabrication of the ASC-2 was deferred until later in Phase III.

NASA GRC is supporting the ASC and ASRG development in a number of key areas that focus on the life and reliability of the technology.

- Reliability and Quality Assurance
- In-house convertor and component testing
- High-temperature materials and structures



Fig. 3. The ASC-0 #1 and #2 in the NASA GRC Stirling Research Laboratory

- Electromagnetic Interference and Electromagnetic Compatibility (EMI/EMC)
- CFD gas bearings modeling
- Organic materials development and characterization
- Magnet aging and characterization
- Support of Lockheed Martin controller development

To provide life and reliability data and performance evaluation on the ASC, GRC ordered four additional hermetic convertors based on the ASC-1 intended for extended

operation in the GRC Stirling Research Laboratory (SRL): A pair of ASC-0 (In718, 650 °C operation) convertors and a pair of ASC-1HS (MarM -247, 850 °C operation) convertors. Further, these early hermetic units would be used to identify development issues, and to develop processing techniques for the later hermetic convertors. A pair of ASC-0 convertors, shown in Fig. 3, was delivered to GRC in December 2006. Initial testing was completed in-air for over 600 hours and is currently operating in a thermal-vacuum environment in GRC's Stirling Research Laboratory. The ASC-0s have accumulated over 2800 hrs of operation as of May 2007. The ASC development convertors currently in operation are shown in Table I. The ASC-1HS pair is scheduled for delivery to GRC in summer 2007 and will undergo extended operation in the thermal vacuum facility.

In April 2007, ASC-1 #4, shown in Fig. 4, completed a series of simulated launch vibration levels at UTC-R. Testing was performed with the ASC producing power in both the axial and lateral directions. Testing was completed at Workmanship (6.8 g_{rms} random) for 1 minute, Flight (8.7 g_{rms} random) for 1 minute. Qualification (12.3 g_{rms} random) for 3 minutes. In addition the ASC-1 #4 was operated at Qualification + 3 dB (17.5 g_{rms} random) for 1 minute. The test configuration included demonstration of an internal FLDT, which is a modification in the design for the ASC-E.

After successful launch simulation testing, ASC-1 #4 along with matching convertor, ASC-1 #3, were delivered to NASA GRC for continuous operation in May 2007. These convertors are now undergoing checkout testing. Testing of two pairs of ASC has been initiated at the NASA GRC SRL, a pair of ASC-0s and a pair of ASC-1s.

In addition, the braze for the displacer joint was developed, electrical feed thru screening was completed, piston and centerport evaluation and



Fig. 4. Sunpower ASC–1 #4 installed on Vibration Table at UTC-R.

TABLEI					
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ASC Development Convertors currently in operation						
Model	Units	Head Material	Thot/Tcold	Power (AC)	Design Features	Comments
FTB	2	Stainless Steel	650 C/ 30 C	85 W	Non-Hermetic	Development Units
ASC-0	2	In-718	650 C/90 C	70 W	Hermetic	Initial Testing @ GRC Feb 07
ASC-1a	2	MarM-247	850 C/90 C	88 W	All MarM-247 HH	On test at Sunpower
ASC-1b	2	MarM-247/In718	850 C/90 C	88 W	Inertia Welded HH	Initial Testing @ GRC May 07



Fig. 5. Sunpower ASC-E to be incorporated into the DOE/Lockheed Martin ASRG EU.

development was completed, regenerator fabrication and procedures were completed as part of the development project. During Phase II, procedures were initiated to prepare for the manufacturability of the ASC-E convertors.

The ASC-E, shown in Fig. 5, is the designation for the convertors that are intended for incorporation into the DOE/Lockheed Martin ASRG Engineering Unit (EU). While the other ASC machines are intended as laboratory units, the ASC-E by design are intended for integration onto an engineering unit of an RPS, thus requiring different interfaces and generator system inputs.

At the outset of the ASC-E design, trade studies were performed by Sunpower, GRC, and Lockheed Martin to determine:

- The heat collector interface with the GPHS
- The Cold-Side Adapter Flange (CSAF) interface with the generator housing/radiator
- Piston position sensor
- Feedthroughs
- Piston centering
- Controller approach
- Launch simulation evaluation

GRC and Sunpower conducted a design review of the ASC-E design in November 2006. The ASC-E design has been frozen and is under configuration control at NASA GRC. Three

ASC-E convertors are being provided as government furnished property to the DOE ASRG project and will be delivered in October 2007. The Phase III ASC hardware being fabricated is shown in Table II.

III. KEY ACCOMPLISHMENTS

Key accomplishments and benefits of the Sunpower ASC development project:

- Phase I FTB demo surpassed performance goal (30 per cent) demonstrating 36 per cent efficiency at 650 °C heater head and 30 °C rejection temperatures,
- Phase II ASC-1 completed and operational surpassed performance goal demonstrating 38 per cent efficiency with 88 W AC power at 850 °C heater head and 90 °C rejection temperatures
- NASA directed use of Sunpower ASC within SRG110 design in March 2006
 - Resulting in significant improvement (X2) of generator specific power
 - From SRG110 ~ 3.5We/kg to ASRG ~ 7.0 We/kg,
- Sunpower ASC-E design review completed in November 2006
- DOE/LM ASRG EU final design review completed in February 2007
- Initial operation and testing of ASCs at NASA GRC initiated in February 2007
- ASC-1 #4 successfully passed launch vibration test at UTC-R in April 2007

IV. ADVANCED STIRLING RADIOISOTOPE GENERATOR (ASRG)

The Sunpower ASC has been substituted into the DOE/Lockheed Martin SRG110 design resulting Stirling Radioisotope Generator (ASRG). [12]

TABLE II

Phase III Advanced Suring Convertors for the DOE/LW ASKG Engineering Unit and Development						
Model	Units	Head Material	Thot/Tcold	Power (AC)	Design Features	Comments
ASC-1HS	2	MarM-247/In718	850 C/90 C	88 W	Hermetic	Delivery Summer 2007
ASC-E	3	In-718	650 C/60 C	75 W	Hermetic	Delivery Oct. 2007 for ASRG EU
ASC-2	4	MarM-247/In718	850 C/90 C	88 W	Hermetic	Delivery August 2008



Fig. 6. The DOE/LM Advanced Stirling Radioisotope Generator Engineering Unit

The in a new generator design, called the Advanced ASRG consists of a beryllium housing, two advanced Stirling convertors, and electronic controller with single fault tolerance design, and one General Purpose Heat Source (GPHS) at each end held by a heat source support with bulk thermal insulation. Thermalto-electric power conversion is provided by two free-piston Stirling engines each integrated with a linear alternator (Stirling convertor) designed in an hermetically sealed pressure vessel. Each Stirling convertor produces AC electrical power which is converted to DC power by the controller.

Currently there are two ASRG design configurations, the ASRG EU, which is currently being developed, uses the 650 °C ASC heater head temperature and a higher specific power ASRG with 850 °C ASC heater head temperature. The ASRG (650) design will be able to deliver 143 We (DC) with a specific power of 7 We/kg at BOL (28 per cent system conversion efficiency). The ASRG EU at 650 °C will use the ASC-E Stirling convertors currently being developed by Sunpower. Lockheed Martin completed a final design review of the ASRG EU using the 650 Stirling convertor in February 2007. The ASRG design, shown in fig. 6 is reviewed in detail in a paper by Richardson [15]. An ASRG using the 850 °C ASC would enable RPS with greater than 8 W/kg specific power and greater heater head design margin [12].

V. CONCLUSIONS

In summary, the technology development for the Sunpower Advanced Stirling Convertor (ASC) has made significant progress: Phase I demonstrated the advanced technologies in the FTB exceeding their original goals; Phase II demonstrated high efficiency (38 per cent) in a high temperature, low mass ASC resulting in projected convertor specific power of ~ 90 We/kg. This resulted in the ASC being selected in March 2006 to be used with the DOE/LM ASRG EU. ASC-Es are being manufactured for the DOE/LM ASRG EU for delivery in October 2007. The system specific power (> 7 We/kg) of the resulting ASRG EU will be a significant improvement over the state-of-practice RTG. Phase III continues the development of the ASC using existing high temperature materials (MarM-247 @ 850 °C) and has made substantial progress, providing significantly improved margins for use with the future ASRG.

Parameter	$ASRG - 650 \degree C$	$ASRG - 850 \degree C$	
Technology	Stirling Convertor (650 °C)	Stirling Convertor (850 $^{\circ}$ C)	
Power per ASRG BOL (We)	143	~ 160	
Power Degradation (%/yr)	0.8 % (power decays with fuel decay)		
Mass per ASRG (kg)	~ 23	~ 19	
Dimensions	Length: 725 mm; Width: 293 mm; Height: 410 mm	TDB	
Number of GPHS Modules	2	2	
Thermal Power (BOL), (Wt)	500	500	
ASRG Specific Power	7.0	~ 8.4	
Controller	Single Fault Tolerant		
Operating Environment	Vacuum and Mars Atmosphere		
Life Requirement	14 yrs mission + 3 yrs storage		

 TABLE IV

 Comparison of ASRG (650 °C) with ASRG (850 °C)

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