



## SUNPOWER ROBUST STIRLING CONVERTOR (SRSC) PROJECT OVERVIEW

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*In October 2017, the team of Sunpower and Aerojet Rocketdyne was awarded a development contract by NASA GRC under NASA's ROSES 2016 Announcement of Opportunity. The contract is in support of the Radioisotope Power Source (RPS) office's goal of developing a robust, dynamic RPS for potential future flight missions. Sunpower's proposed design – the Sunpower Robust Stirling Convertor (SRSC) – implements robustness improvements identified in the point of departure, high performance free-piston Stirling convertor design – the Advanced Stirling Convertor Engineering Unit (ASC-E3). New, key requirements for potential RPS missions have been added to the project, and the expectation is the convertor produced in this contract will enable a 250W to 500W generator. Based on a modular design, the SRSC will enable a range of generators from 250W to 500W with variable levels of redundancy. This paper will focus on Phase II of the SRSC project which began in July 2018, present the SRSC predicted performance, and highlight design improvements made to increase robustness while maintaining high performance and specific power.*

### I. Project Overview

#### I.A. Project Scope

Phase I, which was completed in early 2018, focused on hermetic convertor design and analysis, estimating convertor performance, developing an initial FMECA, and developing verification and compliance matrices.

Phase II which started in mid-2018 includes finalizing hermetic and flanged prototype design details, fabricating two flanged prototype engines and one prototype controller. Also included in Phase II is updating the FMECA and Design Description Document, developing a Flight Maturation Plan and a convertor Test Plan, and implementing Risk Management.

Should the Phase III option be exercised, it may include post-delivery support, data and hardware inspection, and production of additional hardware.

#### I.B. Project Team

Sunpower and Aerojet Rocketdyne (AR) comprise the SRSC project team. Sunpower is the prime contractor while AR is subcontracting to Sunpower.

Sunpower has extensive Free-Piston Stirling Engine (FPSE) expertise, including analysis, design, fabrication and testing, Sunpower also has extensive free-piston machine controls experience and understanding. Sunpower also brings its Advanced Stirling Convertor (ASC) development experience. For this project, Sunpower is tasked with:

- Convertor design, analysis, fabrication, testing, and delivery
- Convertor performance and compliance predictions
- Controller design, fabrication, and delivery
- Program management and reporting.

AR brings its reliability expertise, system integration expertise, RPS and aerospace experience, and extensive materials expertise. Aerojet Rocketdyne tasks include:

- Generator level considerations including power level studies
- Analysis of robustness and reliability (FMECA)
- Development of a Flight Maturation Plan
- Advising on system architecture and considerations
- Advising on system integrator and mission team considerations

#### I.C. Project Schedule and deliverables

The SRSC Design Phase (Phase I) PoP (Period of Performance) was six months, running from October 2017 through April of 2018. The prototype phase (Phase II) PoP is expected to be 18 months, running from July 2018 through December 2019. The Phase III PoP duration is expected to be 12 months and start in January 2020.

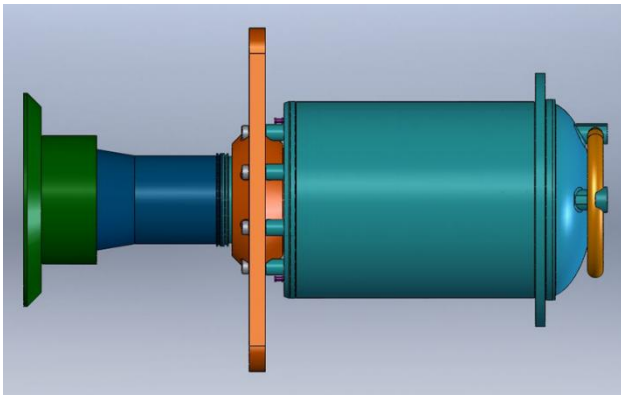
Hardware deliverables in Phase II consist of two non-hermetic SRSC prototypes and a controller capable of operating one or both convertors. Onsite, post-delivery support will be provided early in Phase III. Material procurement and long-lead prototype hardware began immediately after contract finalization for Phase II. Prototype hardware fabrication and processing began at Sunpower and

vendors in October 2018 once design changes identified during the Final Review of Phase I were implemented in engineering drawings. Fixture and test drawings are complete. Sunpower completed test cell setup and shakedown testing in November 2018. Upcoming production milestones are presented in the following figure.

Soft deliverables focus on design definition, analysis, production planning, test data, and programmatic meetings and reporting. SRSC production documentation will draw upon previous

| Milestone                  | SRSC1    | SRSC2    |
|----------------------------|----------|----------|
| Component fab complete     | Apr 2019 | Jul 2019 |
| Front-end assembly         | May 2019 | Aug 2019 |
| 1st operation              | May 2019 | Aug 2019 |
| Operation with controller  | Jul 2019 | Oct 2019 |
| Final Performance test     | Aug 2019 | Nov 2019 |
| Hardware Acceptance Review | Dec 2019 | Dec 2019 |
| Delivery to NASA GRC       | Dec 2019 | Dec 2019 |

ASC-E3 production documents. Redlined ASC-E3 production documents will be used as appropriate. Additional electronic deliverables include updated FMECA, updated Design Description Document, Flight Maturation plan, Test plan, test and inspection data, hardware photographs, and risk register.



## II. SRSC Overview

The SRSC design is of the same power level and overall physical envelope as the ASC. It includes robustness enhancements from lessons learned during ASC development. It also includes changes made to meet new project requirements such as a 5g lateral load requirement and unloaded operation for 10 seconds without damage. The reject temperature capability has also been increased.

The current SRSC design is modeled in the following figure.

Key physical and operating characteristics are presented in the following two tables.

| Physical Characteristics (Flight)  |   |
|------------------------------------|---|
| Mass                               | <ul style="list-style-type: none"> <li>• 3.4kg – convertor, CSAF, external acceptor included</li> <li>• 2.0kg - convertor only</li> </ul> |
| Outer diameter                     | 127mm   |
| Overall length                     | 237mm   |
| Physical Characteristics (Flanged) |   |
| Mass                               | • 7.2kg   |
| Outer diameter                     | <ul style="list-style-type: none"> <li>• 127mm</li> <li>• 182mm (test mounting flange)</li> </ul>   |
| Overall length                     | • 265mm   |

| Nominal Operating Point (BOL, Low Heat) |          |
|---|----------|
| Head temperature                        | 680-720C |
| Reject temperature                      | 100C     |
| Alternator temperature                  | 110C     |
|   |          |
| GPHS heat                               | 244W     |
| Insulation loss                         | 20.6W    |
| Convertor heat input                    | 223.4W   |
| PV power                                | 74.1W    |
| Alternator losses                       | 10.5W    |
| Net output power                        | 63.7W    |

## II.A. SRSC Heritage

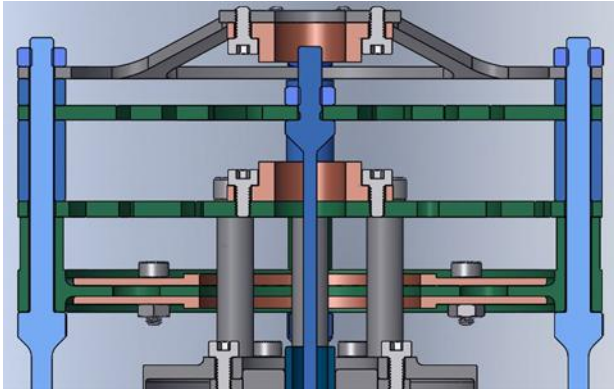
The SRSC design heritage traces back to the initial ASC designed under a National Research Announcement award. However, the point of departure for the SRSC is the most-recent convertor design – the ASC-E3. The ASC-E3 project yielded a total of eight convertors built according to Flight-level production documentation, contamination control, and quality system. Convertors were delivered to NASA GRC for long-term testing and evaluation. ASC-E3 accomplishments include:

- TRL-6 achieved through error-free operation, acceptance vibe, launch vibe, and random vibe tests
- Average thermal efficiency of 40% at BOMLR conditions (63% of Carnot efficiency)

- Seven units completed 2,000 hours of error-free operation as part of NASA GRC independent performance verification
- More than 118,400 cumulative hours of operation at NASA GRC as of May 2018

Relevant accomplishments from ASC builds that preceded the ASC-E3 design include:

- Technology Demonstration Units accumulating more than 181,600 hours of operation as of May



2018

- Engineering Units (ASC-E, E2) accumulating more than 216,100 hours of operation as of May 2018
- Successful environmental testing
  - o Qualification vbe testing (5 units)
  - o Launch vbe testing (3 units)

| Design Feature           | Design Change                             | New Req't | Converter Improvement |          |     |
|--------------------------|---|-----------|-----------------------|----------|-----|
|                          |   |           | Robust                | Reliable | Mfg |
| Regenerator              | Cryocooler production method              | X         | X                     |          | X   |
| Unloaded operation       | Bumpers                                   | X         | X                     |          |     |
| Magnet material          | Material change for high reject operation | X         |                       | X        |     |
| Piston/cylinder material | Material change for high reject operation | X         |                       | X        |     |
| Gas bearing design       | Increased rod bearing capacity            | X         |                       |          |     |
| Piston axial centering   | Piston centering spring                   |           | X                     |          |     |
| Encapsulated magnets     | Encapsulated magnets                      |           | X                     |          |     |
| Robust magnet can        | Thickened can, spider, ribs               |           | X                     |          |     |
| Piston filter            | Gas bearing inlet filter                  |           | X                     |          |     |
| Check valves             | Series check valves                       |           | X                     |          |     |
| Alternator clearances    | Alternator clearances                     |           | X                     |          |     |
| Heater head material     | Material change                           |           |                       |          | X   |

- o EMI testing (2 units)
- o Thermal vacuum testing (2 units)
- Successful durability testing
  - o Axial and lateral centrifuge testing (1 unit)
  - o Start/Stop Cycling test (1 unit)

## II.B. SRSC Design Changes

Design changes incorporated into the SRSC were made for four criteria –respond to new project requirements, increase robustness, increase reliability, or increase manufacturability. Key changes are listed in the following table along with which criteria is addressed.

### II.B.1. Regenerator

Sunpower is currently studying regenerator designs which will ensure no debris are released during operation. Indications are that debris observed in previous regenerator designs were related to fabrication, cleaning and installation processes. The drag force on wires during engine operation creates very little stress (<10 psi). The resonance of a regenerator fiber is also not a concern since the length of wire that is resonant at engine frequency is much longer than the annular width of the regenerator cavity. The planned regenerator production method will follow Sunpower's proprietary cryocooler regenerator production method. The method will be tailored as necessary. The cleaning method, if it is necessary, will also be tailored for the SRSC.

### II.B.2. Bumper and piston centering

A key NASA requirement in the DRPS project is survival of 10 seconds of unloaded operation with no long-term loss of function or capability. Two mechanical features (shown in the following figure) implemented in the SRSC design are known first-contact surfaces (bumpers) between the moving components and the structure, and mechanical axial piston centering. Bumper surfaces are fabricated for flat, face-to-face contact and the material is selected such that no debris is generated during contact. A planar spring provides mechanical, axial piston centering. The mechanical spring's sole function is to ease the startup procedure which previously required DC current to center the piston.

### II.B.3. Loss of Load Tolerant (LLT) Features

In addition to mechanical bumpers, Sunpower has recently developed a pneumatic method of contact avoidance during unloaded operation. Sunpower's patent-pending design is named the Loss of Load Tolerant (LLT) design. Published features of the LLT and be found in U.S. Patent Application 20180112625.

LLT operation has been demonstrated in Sunpower 80W and 1kW class engines. No impacts were observed in an 80W class engine when unloaded at full power. No impacts have been observed to date in 1kW engines when operated with LLT features up to 400 W. Sunpower continues testing in the 1kW to achieve full power.

### II.B.4. Magnet Material Change

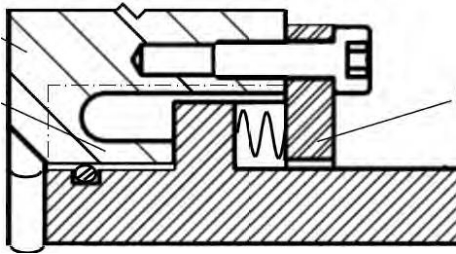
The magnet material has been changed from a Neodymium Iron Boron alloy used in the ASC design, to a Samarium Cobalt alloy to meet the higher reject temperature requirements.

### II.B.1. Increased Gas Bearing Capacity

A new, 5g lateral load requirement was imposed on the ROSES project. This requirement is greater than requirements in the ASC project, and it requires design modification to accommodate. The most straightforward and developed method to meet this requirement was to increase the displacer rod diameter so that its gas bearings have a larger support area. This does result in an overall loss of engine efficiency due to increased pumping losses which comes off of the cycle power. To support 5g lateral load, the displacer rod diameter has been increased from 4.5mm of the ASC to 6.35 mm

#### II.B.1. Cylinder mounting and material change

The installed ASC cylinder geometry was found to be sensitive to the torque applied to the mounting clamp. Because of this, the SRSC will implement an improved mounting technique found in U.S Patent 20180306140 which minimizes distortion to the cylinder caused by mounting torque, charge pressure, or thermal expansions. The following figure shows the mounting geometry presented in the patent.



Additionally, with the new reject temperature requirement of 175°C, the engine cylinder and piston material have been changed to titanium, which is the same material as the magnet can.

#### II.B.1. Gas bearing check valve and filter

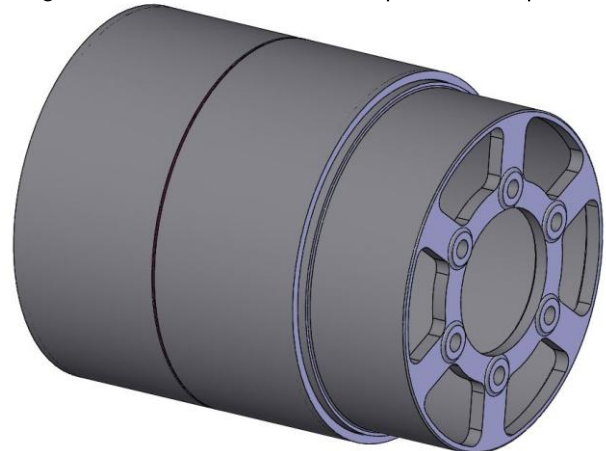
Sunpower convertor designs incorporate gas bearings on the moving components. Gas bearings simplify convertor mechanical design as well as reduce assembly difficulty. The use of gas bearings also largely reduces the number of single point failures in the convertor. There are concerns within the RPS community that gas bearings could be compromised by debris in the working space. Though isolated, there have been instances of compromised gas bearings due to debris entering the gas bearing system and lodging under the check valve. The check valve fails to seal completely and reduces the gas bearing strength. Two features have been added to the SRSC design to make the gas bearing system robust to debris. First, a filter has been added to the inlet of the gas bearing system to prevent debris from entering the system. Second, a second check valve (in series) has been

added to the system. These modifications require three cascading failures by multiple pieces of debris - filter failing to prevent debris, first check valve failing to seal, and second valve failing to seal - to compromise the gas bearings.

#### II.B.1. Encapsulated magnet can

During the ASC-E3 program, two convertors were unintentionally driven to severe collisions during offsite testing. The high impact, driven collisions caused permanent deformation to the magnet can assembly. The deformation led to contact and persistent rubbing between the magnets and laminations which caused debris generation. Design modifications to increase the magnet can assembly robustness to contact have been developed and incorporated by Sunpower in the SRSC design.

The design changes shown in the following figure are a) a thin, split sleeve to cover the magnets, b) ribs at each end of the magnets, c) thicker magnet can structure, and d) a thicker magnet can hub. The thin, split sleeve prevents



|                | Head Temp (C) | Reject Temp (C) | Heat In (W <sub>in</sub> ) | Output Power (W <sub>e</sub> ) | Efficiency (%) | Efficiency Req. (Goal) (%) | Specific Power (W <sub>e</sub> /kg) |
|----------------|---------------|-----------------|----------------------------|--------------------------------|----------------|----------------------------|-------------------------------------|
| Nominal        | 720           | 100             | 223                        | 65.3                           | 29.2           | 24, (28)                   | 32.6                                |
| 125 Reject     | 720           | 125             | 223                        | 63.3                           | 28.4           |                            | 31.6                                |
| High Reject    | 720           | 175             | 223                        | 52.1                           | 23.3           |                            | 26                                  |
| 2/3 Heat Input | 720           | 100             | 149                        | 41.1                           | 27.6           |                            | 20.6                                |
| 1/2 Heat Input | 720           | 100             | 112                        | 28.7                           | 25.7           | 20                         | 14.3                                |

direct contact between laminations and sintered magnets. The thicker magnet can, ribs, and thicker hub result in a stiffer assembly that is more robust against collisions. The alternator running clearances have also been increased.

#### II.B.1. Heater head material change

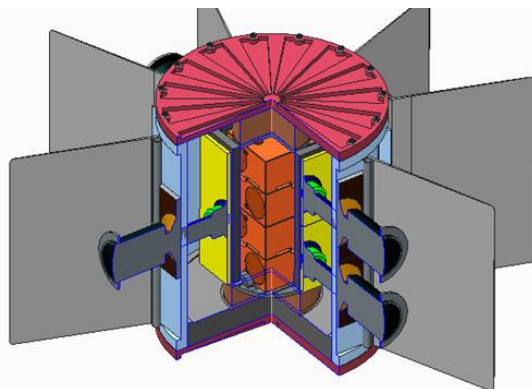
Previous convertor designs selected MarM for the heater head material due to its high temperature strength capabilities. However, MarM has several

drawbacks including low availability with the desired properties, limited material property data, long-lead times, and long costly processing. To eliminate these concerns and reduce schedule and cost risks, Aerojet Rocketdyne have recommended Haynes 230 alloy. AR have extensive experience with Haynes 230. Haynes 230 is more widely available, better researched, less costly, and requires less processing than MarM.

## II.C. SRSC Performance Predictions

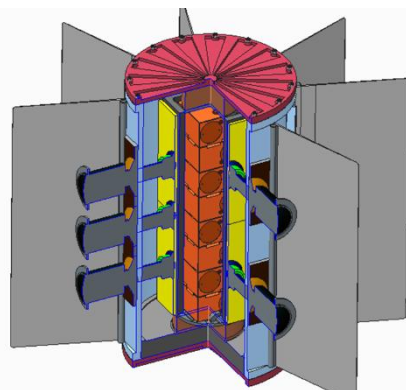
The point of departure design – ASC-E3 - convertors all produced slightly over 40 percent thermal conversion efficiency. New requirements levied on the SRSC (higher reject temperature, increased lateral load requirement), design changes to increase robustness, and a lower nominal operating temperature for the heater head have reduced overall convertor efficiency by approximately 10 percentage points. The projected efficiency of the SRSC is 29.2 percent. However, this exceeds the required efficiency of 24% and the programmatic goal of 28%. This efficiency remains essentially constant over the 17-year mission requirement. AC output power from each SRSC convertor is projected to be 67W at the beginning of mission dropping to 56.2W (due to degradation of the heat source and available heat) after 17 years. The following table presents predicted performance of the convertor at various operating points.

Aerojet Rocketdyne performed convertor and generator power level trade studies during Phase I. They also developed initial thermal simulations, heater head integration, and rejector integration studies to help inform SRSC design decisions. As a natural extension of these studies, Aerojet Rocketdyne developed notional generator layouts which are depicted in the following two figures. The layouts are developed based on integer pairs of convertors and GPHS modules. The first figure shows a 250W generator with 50% redundancy.



The second shows a notional 500W generator with 25% redundancy.

## II. CONCLUSIONS



Sunpower's SRSC design offers improvements in robustness, reliability, and manufacturability based on lessons learned from the point of departure design – the ASC-E3. The SRSC is expected to be compliant with all program requirements and goals as shown in the following table.

Additional improvements in manufacturability have been incorporated based on Aerojet Rocketdyne's materials expertise and Sunpower's cryocooler manufacturing experience. Furthermore, the SRSC design offers technical maturity by

| Category                  | Requirement  | Goal   | Current Estimate |
|---------------------------|--|--|------------------|
| Design life               | 20 years continuous operation                            |  | Compliant        |
| Power output              | Enables 200-500W generator                               |  | Compliant        |
| Start-stop cycles         | Capable of min 150 cycles                                |  | Compliant        |
| Launch vibration          | Survive, no long-term power loss                         |  | Compliant        |
| Static acceleration       | Static and random vibs exposure, no long-term power loss |  | Compliant        |
| Performance degradation   |  | Power degradation < 0.5%/yr                  | Compliant        |
| T/E conversion efficiency | ≥ 24% at Trej ≥ 100C                                     | ≥ 28% at Trej ≥ 100C                         | 29%              |
| Partial power op          | ≥ 20% efficiency at half power                           |  | 27%              |
| Head operating temp       | < 1000C  |  | Th = 720C        |
| Reject operating temp     | ≥ 100C to meet efficiency req't                          |  | Compliant        |
|                           | Operation 20 - 175C                                      |  | Compliant        |
| Thermal energy input      | Accept heat from GPHS                                    |  | Compliant        |
| Atmospheres               | Earth, argon, vacuum, Mars, Titan                        |  | Compliant        |
| Radiation environment     |  | No power loss after 300krad exposure         | Compliant        |
| EMI                       |  | DC magnetic field                            | Compliant        |
| Autonomy                  |  | No set point adjustments during launch       | Compliant        |
|                           |  | No set point adjustments during static accel | Compliant        |
| Loss of load              | 10 second loss of load at full power, no power loss      |  | Compliant        |
| Transmitted forces        | < 10N transmitted to spacecraft                          |  | Compliant        |
| Specific power            | > 20W/kg (convertor only)                                |  | ~33 W/kg         |
| Size                      | Generator fits DOE cask                                  |  | Compliant        |
| Manufacturability         |  | Utilize proven MFG methods                   | Compliant        |
| Flight instrumentation    |  | No sensors required for mission              | Compliant        |
| Prototype instrumentation | Direct measurement of Th, Tr, alternator, Xp, Xd         |  | Compliant        |

drawing upon the successes of the ASC-E3 program (achieving TRL-6, demonstrating high efficiency, completing Independent Verification and Validation testing at GRC, developing Flight-level quality system and production documentation, etc.) and ASC development (durability, vibration, environmental, and life testing).

As shown in the generator power level trade study, the modular approach based on integer pairs

of convertors and GPHS modules can be implemented for generators with nominal outputs in 125W increments with varying levels of redundancy. The modular approach offers potential missions variability in power level and redundancy options based on mission needs.

The Sunpower, Aerojet Rocketdyne team has completed approximately one third of the Phase II period of performance. Sunpower's primary focus at this time is production of prototype hardware and preparation for convertor assembly and testing. The first convertor is anticipated to be operational in Q2 of CY2019. The second SRSC prototype will be processed serially with the first and is expected to be operational in Q3 CY2019. Controller development will occur in parallel with the convertor builds and operation with the convertors is planned for Q3 CY2019.

#### **ACKNOWLEDGMENTS**

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