Sunpower Robust Stirling Convertor (SRSC) Phase II Overview and Phase III Status

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Project Overview

The SRSC Project is one of three Phase II contracts awarded as part of the DRPS project through the ROSES funding opportunity

SRSC Project Team

- Sunpower
  - *SRSC detailed design, simulation, and modeling*
  - *SRSC prototype production*
  - *Test plan and verification plan development*
  - *Convertor-level trade studies*

- Aerojet Rocketdyne
  - *Materials studies and selection*
  - *FMECA*
  - *Flight Maturation Plan*
  - *Generator concept design and trade studies*

SRSC Design

Point of Departure design – Advanced Stirling Convertor

Design Change trade space

- New program requirements – Design changes made to address new program requirements
- Increase robustness – Design changes made to reduce or eliminate risk of life-limiting damage or permanent power loss from operation outside of the expected environments
- Increase Reliability – Design changes made to increase the likelihood of error-free operation over the planned mission life (17yrs plus storage)
- Increase manufacturability – Design changes made increase production subassembly yield, reduce testing duration, reduce assembly duration thereby reducing overall convertor cost
- Build upon cryocooler heritage – Implement lessons learned from spaceflight cryocooler business and commercial business

SRSC Design

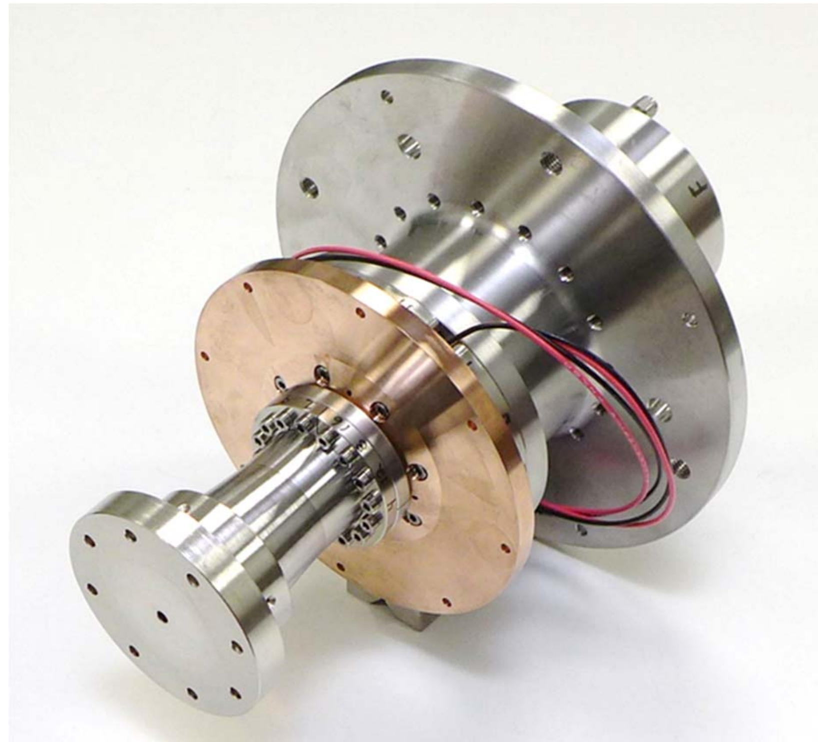
- Cryocooler flights (CryoTel CT-S)
  - *Freezers for sample preservation on ISS*
    - GLACIER – ~50 launches to date (2 CT-S per freezer, some launched multiple times)
    - POLAR – ~20 launches to date (1 CT-S per freezer)
    - RAPID FREEZE – RRM3 launch

- RHESSI Satellite (M77 cryocooler)
  - *Launched Feb 2002 with planned mission duration of 2 years*
  - *Decommissioned in 2018 (16 year mission)*

- Other applications
  - *Balloon – COSI, SPIDER, GRIPS*
  - *Airborne – CHIRP, AVIRIS, Hytes*
  - *Ground-based telescopes*

Phase II Overview

- Scope
  - *SRSC prototype production*
  - *SRSC detailed design, simulation, and modeling*
  - *Test plan and verification plan*
  - *Convertor-level trade studies*
  - *Correlate simulations and models with hardware test data*
  - *Gas Bearing Test Rig design*



- Milestones

Milestone	SRSC-1	SRSC-2
First operation	Jul 2020	Apr 2020
Unloaded test	Aug 2020 (x3)	Apr 2020 (x2)
Thermal cycling	Aug 2020	May 2020
Final performance test	Sep 2020	May 2020
Government Acceptance	Sep 2020	Jun 2020
Delivery	Oct 2020	Oct 2020
First operation at GRC	Mar 2021	Mar 2021

SRSC design features compared to POD

Design Feature	Design change	New Req't	Convertor Improvement		
			Robust	Reliable	Mfg
Regenerator	Production method	✓	✓		✓
Unloaded operation	Bumpers	✓	✓		
Magnet material	Material change for high reject temperature change	✓		✓	
Piston/Cylinder material	Material change for high reject operation and CTE match	✓		✓	
Gas bearings	Rod bearing capacity increased	✓			
Piston Centering	Piston centering spring		✓		
Encapsulated magnets	Encapsulated magnets		✓		
Robust magnet can	Thickened magnet can, spider, stiffening ribs		✓		
Piston filter	Gas Bearing inlet filter		✓		
Check valves	Series check valves		✓		
Alternator running clearances	Alternator clearances		✓		
Heater Head	Haynes material				✓

SRSC builds on heritage of ASC while incorporating design improvements that meet new requirements, address lessons learned, address community concerns, increase reliability and increase robustness.

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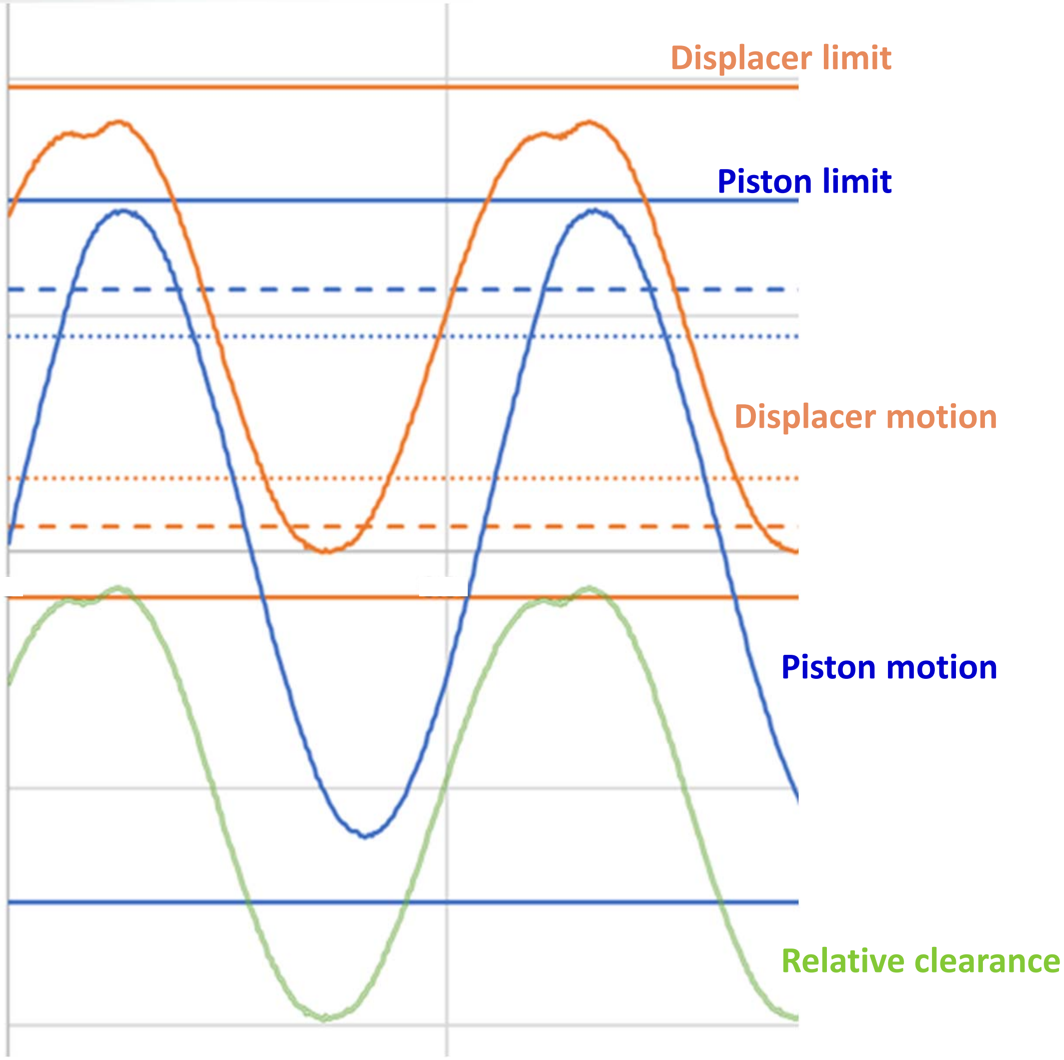
SRSC Design Implementation



Loss of Load Tolerant (LLT) operation

- Sunpower independently developed and patented method of collision avoidance during unloaded operation
  - *Enables hot swap for controller cards (fault protection)*
  - *Reduces complexity of fueling process*
  - *Prevents internal damage upon loss of load condition*

SRSC Design Implementation

Heater Head

- Material change to Haynes alloy as recommended by Aerojet Rocketdyne
- Significant improvement in production compared to heritage material (MarM)
  - *Reduction in lead time and cost*
  - *Yield appears to have increased*

Regenerator

- Debris free design – no sintering no exposed cut surfaces
- New production method (wrapped) has significantly reduced production time and increased yield compared to ASC method

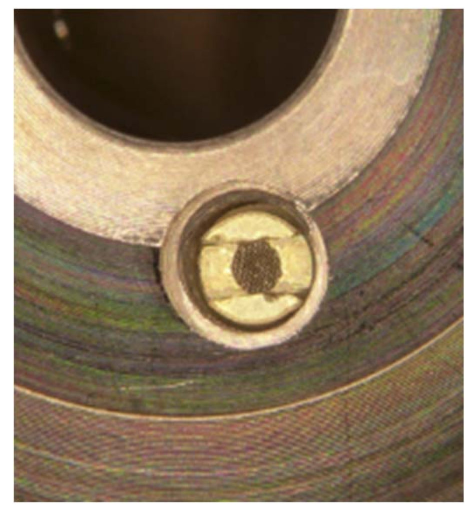
SRSC Design Implementation

Encapsulated magnet can assembly

- First demonstrated under Advanced Stirling Convertor technology maturation efforts
- Robust structure to protect against collisions
- Magnet encapsulation eliminates possibility of magnet rubs/debris generation

Gas bearing inlet filter

- First demonstrated under Advanced Stirling Convertor technology maturation efforts
- First used in production in Sunpower cryocoolers
- Filter at entrance of gas bearing system reduces/eliminates FOD concerns



SRSC Design Implementation

Piston centering spring assembly

- Simplifies controller architecture, reduces overall controller complexity

Piston/cylinder material

- Eliminates localized CTE mismatch between piston and cylinder
  - *Eliminates pinch points induced by CTE mismatch*
  - *Maintains profile and running clearances across the range of operating conditions*

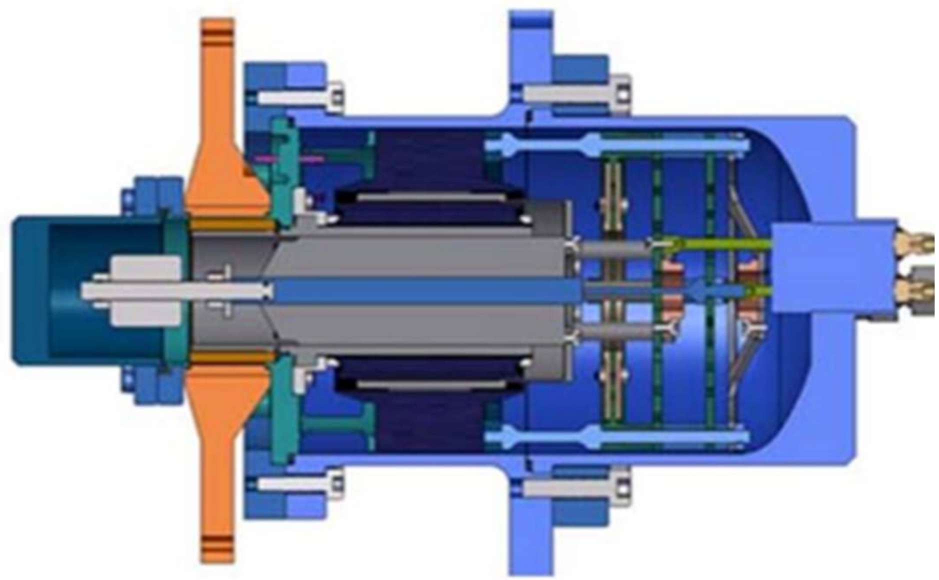
Series Check valves

- Redundant check valve incorporated into gas bearing system
  - *Eliminates single point failure from convertor design (Check valve)*
  - *Increases robustness of gas bearing system*
  - *Maintains existing envelope of piston subassembly*

SRSC Design Implementation

Gas Bearing Test Rig (GBTR)

- Piston is driven by external voltage and displacer response is observed to evaluate gas bearing capacity
- Demonstrated static loading from 2g to 5g
- Data generated from testing has been correlated with simulation models and has helped refine models



Opportunity – The GBTR may be implemented into production to directly verify production gas bearing capacities

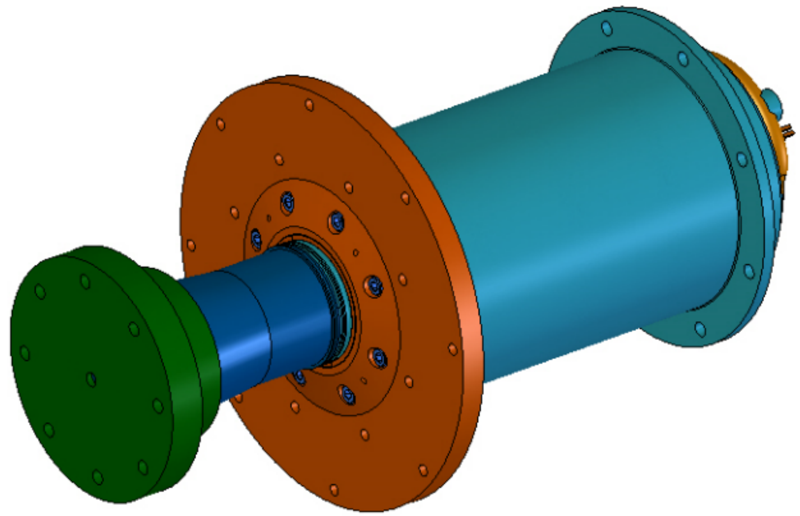
SRSC 1, SRSC 2 performance

Category	Requirement	Goal	SRSC 1	SRSC 2
Design life	20 years of continuous operation at full power		Compliant	Compliant
Convertor power output	Enables a 200 to 500 W_e generator		Demonstrated	Demonstrated
Start-stop cycles	Capable of 150 start-stop cycles		Demonstrated	Demonstrated
Launch vibration	No permanent effect from launch vibe		Compliant	Compliant
Static acceleration	Capable of exposure to static and quasi-static accel with no permanent effect on performance:		Compliant	Compliant
Performance degradation		Power decreases <0.5 % per year	Compliant	Compliant
Thermal-to-electric conversion efficiency	≥ 24% with ≥100°C reject	≥28% with ≥100°C reject	21.4%	22.6%
Partial power operation	Maintains ≥ 20% efficiency at 50% of design output power		17.3%	17.1%
Hot-end operating temperature	< 1000 °C		Th=720°C	Th=720°C
Cold-end operating temperature	• Requires no less than 100 °C to meet efficiency		Compliant	Compliant
	• Operation between 20 and 175 °C		Demonstrated	Demonstrated
Thermal energy input	Designed to accept heat from an integer number of GPHS		Compliant	Compliant
Atmospheric environment	Operation in Earth, Ar, vacuum, Mars Titan atm.		Compliant	Compliant
Radiation		No loss of performance after exp to 300 krad	Compliant	Compliant
EMI		DC magnetic field	Compliant	Compliant
Autonomy		• No operational adjustments during launch	Compliant	Compliant
		• No adjustments needed during static accel	Compliant	Compliant
Tolerance of loss of electrical load	Capable of loss of electrical load at full power for 10 seconds, without any permanent effect on performance		Demonstrated	Demonstrated
Transmitted forces	Enables a generator that reduces transmitted forces to the spacecraft to less than 10 N		Compliant	Compliant
Specific power (W/kg)	> 20 W/kg (convertor only)		25 W/kg	25 W/kg
Size	Enables a generator design that will fit in the DOE shipping container:		Compliant	Compliant
Manufacturability		Utilizes proven and effective MFG approaches	Demonstrated	Demonstrated
Instrumentation necessary for flight convertor		Enables a long-life generator without the need for long-life sensors on the convertor(s)	Compliant	Compliant
Performance measurement	Direct measurement of Th, Tr, Alternator, Xp, Xd. Not hermetic		Demonstrated	Demonstrated

Phase III Overview

Phase III overview

- Scope
  - *Hermetically sealed design*
  - *Incorporate lessons learned from Phase II*
  - *Production of SRSC 3, SRSC 4*



- Planned Milestones

Milestone	SRSC-3	SRSC-4
Production design approval	Nov 2020	Nov 2020
First operation	Jun 2021	Sep 2021
Unloaded test	Jul 2021	Oct 2021
Thermal cycling	Jul 2021	Oct 2021
Final performance test	Aug 2021	Nov 2021
Government Acceptance	Aug 2021	Nov 2021
Delivery	Sep 2021	Dec 2021
First operation at GRC	TBD	TBD

Phase III "Design" tweaks

- Inspection - Sunpower is developing a 3D inspection method to characterize running pairs (cylinder/displacer and cylinder/piston) dimension and profile
  - *Will provide detailed mapping of running surfaces and their fits over the entire stroke*
  - *Enables tighter tolerance requirements (performance improvement)*
  - *Reduces iterative processing time*

- Manufacturability - Engage Phase II component suppliers with lessons learned
  - *Higher yield and more consistent parts*
  - *Net result is savings in processing time*

- In-process gas bearing capacity characterization – Using the Gas Bearing Test Rig, validate production hardware gas bearing capacity meets requirements (in-process check).

Phase III anticipated compliance

Category	Requirement	Goal	SRSC 3	SRSC 4
Design life	20 years of continuous operation at full power		Compliant	Compliant
Convertor power output	Enables a 200 to 500 W_e generator		Demonstrated	Demonstrated
Start-stop cycles	Capable of 150 start-stop cycles		Demonstrated	Demonstrated
Launch vibration	No permanent effect from launch vibe		Compliant	Compliant
Static acceleration	Capable of exposure to static and quasi-static accel with no permanent effect on performance:		Compliant	Compliant
Performance degradation		Power decreases <0.5 % per year	Compliant	Compliant
Thermal-to-electric conversion efficiency	≥ 24% with ≥100°C reject	≥28% with ≥100°C reject	25.0%	25.0%
Partial power operation	Maintains ≥ 20% efficiency at 50% of design output power		Compliant	Compliant
Hot-end operating temperature	< 1000 °C		Th=720°C	Th=720°C
Cold-end operating temperature	• Requires no less than 100 °C to meet efficiency		Compliant	Compliant
	• Operation between 20 and 175 °C		Demonstrated	Demonstrated
Thermal energy input	Designed to accept heat from an integer number of GPHS		Compliant	Compliant
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Performance measurement	Direct measurement of Th, Tr, Alternator, Xp, Xd. Not hermetic		Demonstrated	Demonstrated

Key capability demonstrations

Design Feature	Capability	New Req't	Convertor Improvement			Demonstration	
			Robust	Reliable	Mfg	Phase II	Phase III
Regenerator	Production method	✓	✓		✓	✓	
Unloaded operation	Loss of Load Tolerance (LLT), bumpers	✓	✓			✓	
Magnet material	Material change for high reject temperature change	✓		✓		✓	
Piston/Cylinder material	Material change for high reject operation and CTE match	✓		✓		✓	
Gas bearings	Rod bearing capacity increased	✓				✓	
Specific power	>20W/kg	✓				✓	
Piston Centering	Piston centering spring		✓			✓	
Encapsulated magnets	Encapsulated magnets		✓			✓	
Robust magnet can	Thickened magnet can, spider, stiffening ribs		✓			✓	
Piston filter	Gas Bearing inlet filter		✓			✓	
Check valves	Series check valves		✓			✓	
Heater head	Haynes material				✓	✓	
Convertor performance	Efficiency, power						✓
Hermeticity	Hermetic welds, seals			✓			✓
Manufacturability	Repeatable production, maintain cost effectiveness				✓		✓

Acknowledgements

Radioisotope Power Systems Program

Dynamic Radioisotope Power Sources (DRPS) Project Team

RADIOISOTOPE POWER SYSTEMS

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AEROJET ROCKETDYNE

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