Sunpower Robust Stirling Convertor (SRSC)

Dynamic Power Convertor Technology for Space Power Generation Technical Interchange Meeting

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Prepared by Sunpower, Inc (Athens, OH) and Aerojet Rocketdyne (Canoga Park, CA)

Discussion topics

- Project overview
  - *Phase I team overview, scope, accomplishments*
  - *Phase II and III overview*
- Convertor point of departure design
  - *ASC history*
  - *ASC-E3 accomplishments*
  - *ASC Technology Assessment effort*
- SRSC Design
  - *Trade Studies*
  - *Detailed Design*
- SRSC performance predictions and compliance with requirements
- Generator concepts
- Summary

Phase I Project Team

Project team

- Sunpower Key Personnel
  - *Gary Wood – Sunpower FPSE Technical Leader*
  - *John Stanley – Mechanical Engineer*
  - *Y.S. Kim – Mechanical Engineer*
  - *Todd Cale – Drafting Supervisor*
  - *Ezekiel Holliday – Sunpower Electrical Engineering Technical Leader*
  - *Josh Collins – Program Manager*

- Aerojet Rocketdyne Key Personnel
  - *Bill Otting – Program Manager*
  - *Dan Matejczyk – Materials*
  - *Mike Azizi – FMECA Lead*

Sunpower

Sunpower background

- Free-Piston Stirling Engine invented by William Beale, professor at Ohio University in 1964.
- Sunpower incorporated in 1974
- Purchased by Ametek in Dec 2012
- Business focus technologies
  - *Free-piston Stirling cryocoolers*
  - *Free-piston Stirling engines*
- Headquarters in Athens, OH
  - *Facility with onsite:*
  - *R&D (engineering, drafting, technician, etc.)*
  - *Cryocooler manufacturing,*
  - *Machine shop,*
  - *Quality Assurance/Quality Control*

Sunpower business lines

Cryocoolers





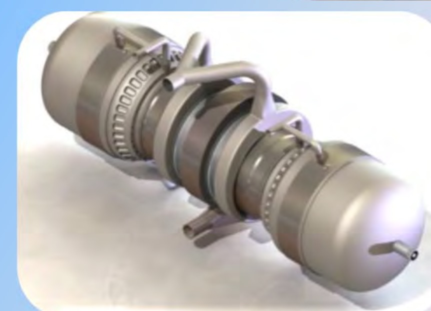
Commercial Development





Government Contracts



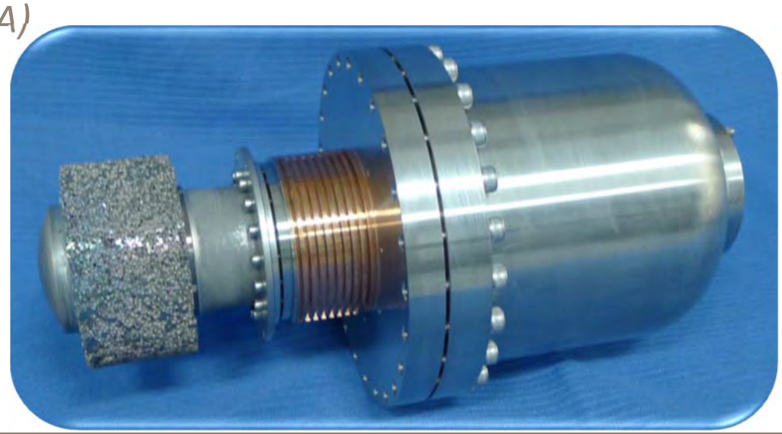



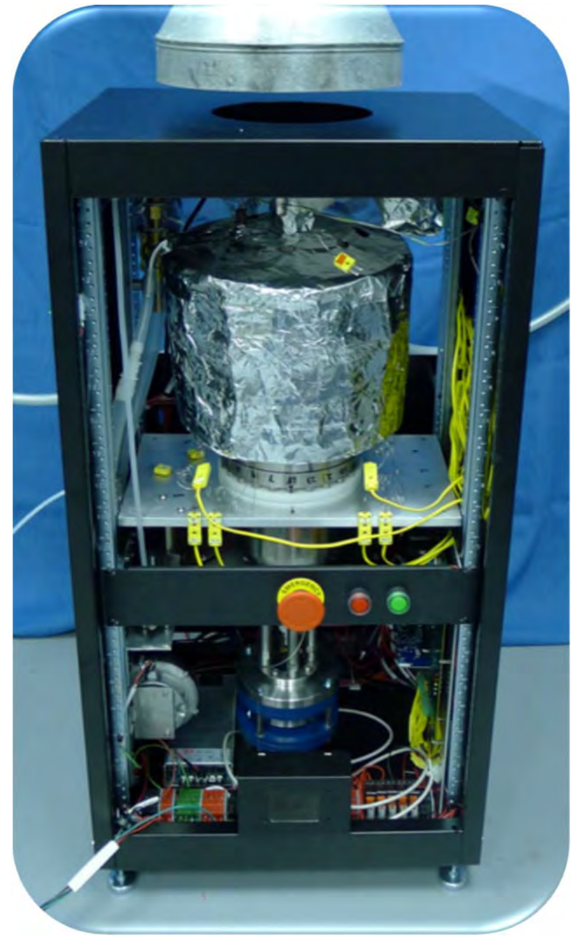
SP Relevant projects – 80W class convertors

- Advanced Stirling Convertor (ASC)
  - *80W class FPSE developed with NASA through NRA contract beginning in 2003*
  - *Adopted for DOE Flight contract as subcontractor to LMSSC*
  - *A total of 30 convertors (six models) delivered to NASA GRC*
  - *ASC-E3 design - Total of 8 convertors delivered to NASA GRC*
    - Final convertor (ASC-E3 #9) delivered in Dec 2015
- NASA Kilopower
  - *80W class convertor tailored for use in Kilopower project*
- DoD 80W variant
  - *Tailored interface, heat source, performance specification*
  - *Commercial customer with military application*
  - *Plan to produce 2 engines in 2018*

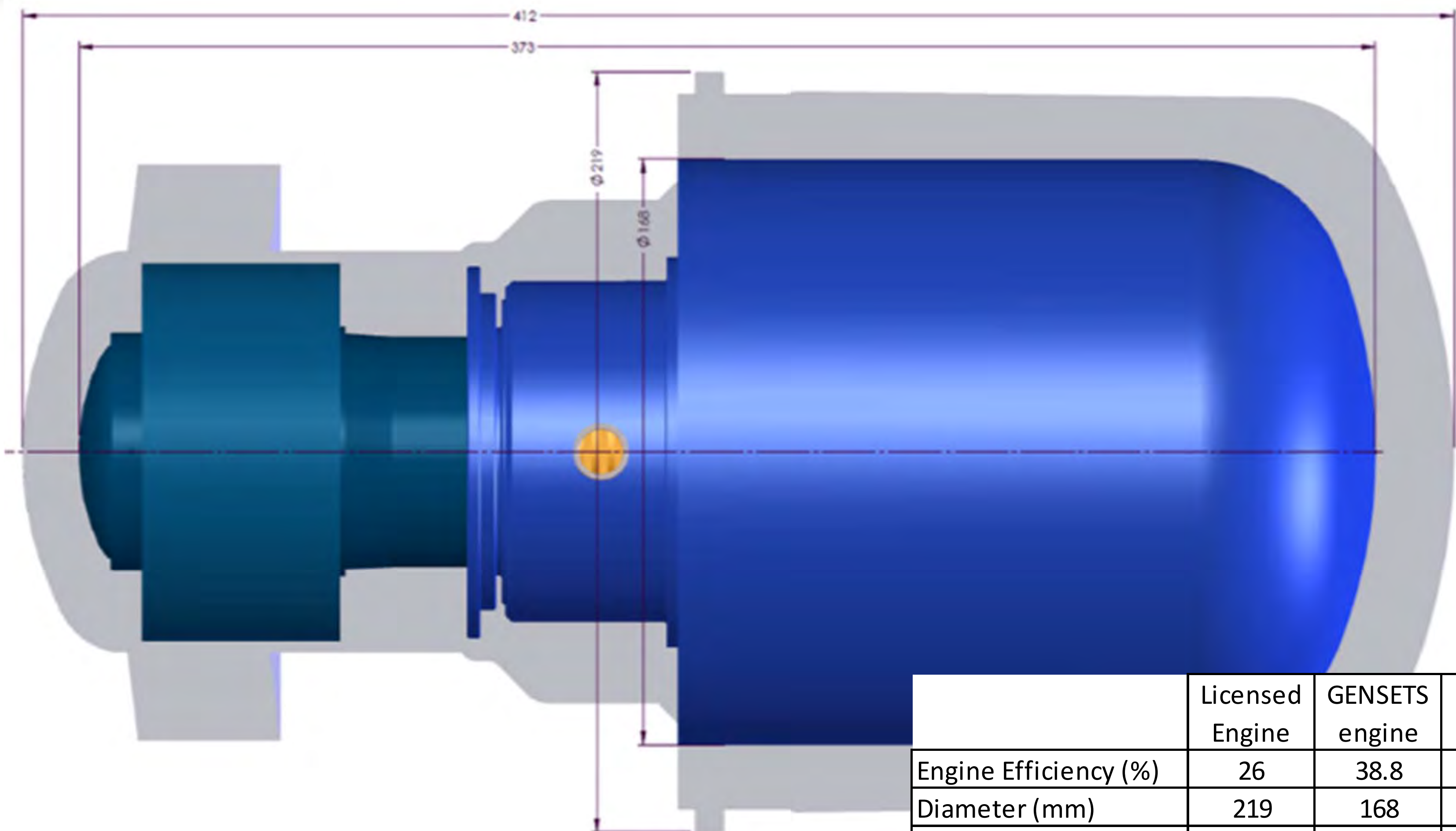
SP Relevant projects – 1kW commercial FPSE

- Next generation, 1kW engine (ARPA-E GENSETS program)
  - *Developed for low-cost entry into US CHP market*
  - *Incorporates advancements demonstrated in R&D programs*
  - *Incorporates lessons learned from successful technology transfer and commercialization in European microCHP and linear compressors*
  - *Teamed with Aerojet Rocketdyne and Precision Combustion, Inc*
- Program Targets
  - *1kW output power, 40% thermal to electric system efficiency*
  - *$3000 consumer cost in volume production (100k units)*
  - *>10-year system life, with scheduled BOP maintenance*
  - *Minimal combustion emissions*
  - *System noise <55 dB(A)*
  - *System mass <150kg*





Gen1 Engine (Grey) vs GENSETS Engine (Blue)



	Licensed Engine	GENSETS engine	Change
Engine Efficiency (%)	26	38.8	49%
Diameter (mm)	219	168	-23%
Overall Length (mm)	412	373	-9%
Mass (kg)	32	23	-28%
Specific Power (W/kg)	31	43	39%

SP Relevant projects - Flight cryocoolers

- Cryocooler flights (CryoTel CT-F)
  - *Freezers for sample preservation on ISS*
    - GLACIER – 49 launches to date (2 CT-F per freezer, some launched multiple times)
    - POLAR – 17 launches to date (1 CT-F per freezer)
    - RAPID FREEZE – RRM3 launch
- RHESSI Satellite
  - *Launched Feb 2002 with planned mission duration of 2 years*
  - *Continues scientific mission, more than 16 years*
  - *Incorporates Sunpower's M77 cryocooler to cool Germanium detector instruments*
- Other applications
  - *Balloon – COSI, SPIDER, GRIPS*
  - *Airborne – CHIRP, AVIRIS, Hytes*
  - *Ground-based telescopes*
- AS9100 certification in process to increase space cryocooler business
  - *Certification complete in Q3 2018*
  - *Directly applicable to future space engine business*

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AR Relevant projects overview

AR Advanced Power Sys – relevant programs

ISS Li-Ion Battery Replacement

SNC Dream Chaser CRS2 Electric Power System

- Power Distribution Units, Power Converters, & Batteries

Radioisotope Power Systems

- Dynamic Power Converter for RPS – ROSES
- Previous - Advanced Stirling Convertor (ASC) program
- MMRTG Production
- Enhanced MMRTG (eMMRTG) Development
- Previous – Dynamic Isotope Power System (DIPS)

Solar Electric Propulsion (SEP)

- Evolutionary Xenon Thruster (NEXT-C)
- Next Space Technologies for Exploration Partnerships (NextSTEP)
- Advanced EPS (AEPS)
- Habitat (NextSTEP-2 / Power and Propulsion Element)

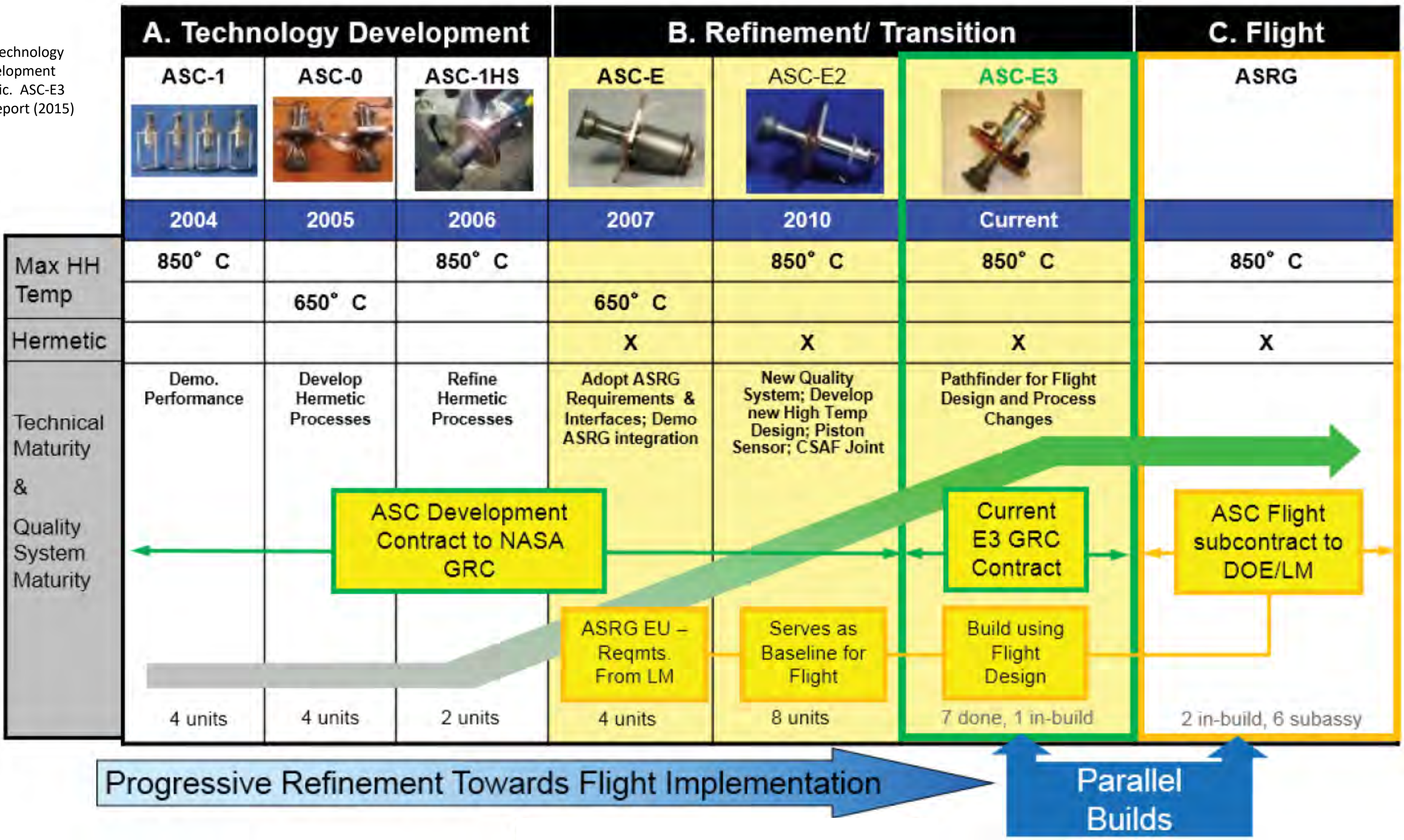
High Temp. Components for ARPA-E Stirling

Convertor design overview

Advanced Stirling Convertor (ASC) Point of Departure Design

ASC history

ASC Technology development graphic. ASC-E3 Final Report (2015)



SRSC design is rooted in ASC heritage but implements lessons learned and design improvements.

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ASC hardware accomplishments

Extended Operation Testing - conducted at GRC's Stirling Research Laboratory

Convertors	Cumulative Operation (as of May 2018)
Tech. Demo. Units (ASC-0, ASC-1, ASC-1HS, ASC-L)	>181,600 hours (20.7 years)
Engineering Units (ASC-E & ASC-E2)	>216,100 hours (24.7 years)
Flight pathfinders (ASC-E3)	>118,400 hours (13.5 years)
Total ASC	**>516,100 hours (58.9 years)**

Provider	Test Article	Hrs of Operation (As of April 9, 2018)
Sunpower, Inc.	ASC-E3 #9 & #4*	13,412 / 27,370
	ASC-E3 #6* & #8	20,513 / 16,364
	ASC-E3 #3	22,113
	ASC-0 #3*	72,369
	ASC-L*	34,932

* Completed random vibe testing as part of life certification

ASC-E3 Operations at GRC's SRL

GRC Cumulative ASC operation >50 years and counting

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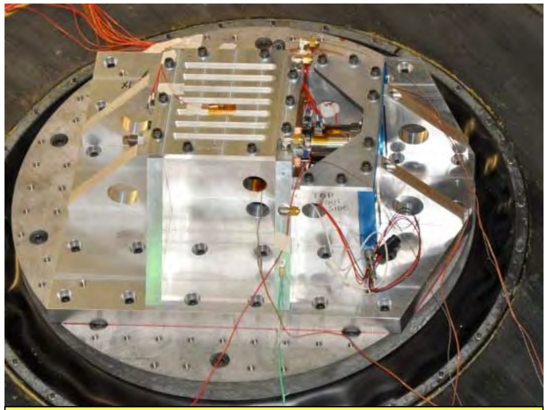
ASC hardware accomplishments

Environmental Testing

Test	ASC Units
Qualification Level Vibration	ASC-E #1 ASC-E #2 & #3 (as part of ASRG EDU on controller) ASC-E2 #2 ACC-E2 #8 - multiple exposures
Launch Level Vibration	ASC-E #4 ASC-E3 #4 ASC-E3 #6
EMI	ASC-E2 #1 & #2
Thermal Vacuum	ASC-1 #1 & #2
Durability Tests	
Centrifuge Acceleration (axial and lateral)	ASC-E2 #2
Start/Stop Cycling (accelerated tests)	ASC-E2 #8

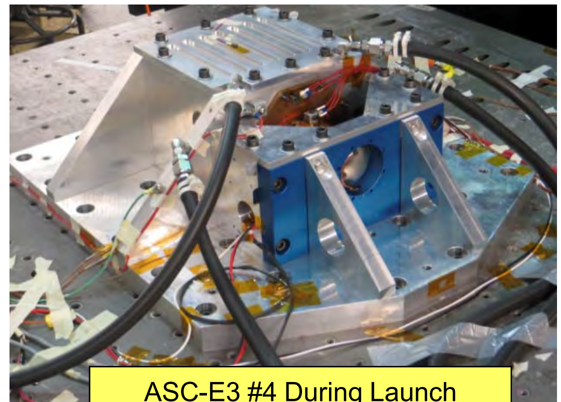

Centrifuge Test Facility at CWRU


Vibe Testing at GRC SDL

ASC-E3 highlights

- Seven ASC-E3 convertors have successfully passed 2,000 hours of error-free operation as part of GRC independent performance verification testing
- Delivered convertors demonstrate design has successfully addressed power fluctuation concerns
- The average thermal efficiency of the delivered ASC-E3 units is 40% at Beginning Of Mission (BOM) Low Reject (LR) conditions
  - ~63% Engine Carnot efficiency
- ASC-E3 design achieved TRL-6 through a combination of error-free operation, flight acceptance vibration testing, and launch simulation vibration testing (ASC-E3 #4 and ASC-E3 #6)

Completed Flight-Like ASC-E3 Pair 3



ASC-E3 #4 During Launch Vibration Testing

ASC Technology Assessment (ASC-E3 Project Task)

Technology assessment background

Technology Assessment

- Development and testing task undertaken near the end of the ASC-E3 program.

Purpose

- Identify and evaluate areas of improvement (primarily design changes) that can be implemented without significant development and redesign that will improve the convertor **reliability and robustness**
  - ***Robustness*** *defined as tolerance to limited off-nominal operation without sacrificing life*
  - ***Reliability*** *defined as long-life operation at nominal conditions (ex. BOM LR)*
- Implement Lessons Learned from ASC-E3 and ASC-F projects
- Secondary goal to identify opportunities to make production more efficient (cost, yield, and/or schedule benefits)

Technology assessment

Why?

- NPAS report, RPS presentations, and Stirling technical community indicate that ASRG requirements and trade studies chose to push performance at the expense of convertor robustness and reliability
- ASRG-EU2 investigation root cause – controller instability created internal collisions and exposed the need for increased convertor robustness to protect against externally imposed, off-nominal operation

Groundrules

- Based on time and budget constraints, design changes were limited to the current ASC envelope
- Suggestions requiring long-term development and design effort will be recorded but not pursued at this time
- Power loss to accommodate areas of improvement is acceptable if the improvements significantly impact reliability and robustness

Technology assessment results

Issue addressed	Design modification	Results	Performance Delta (BOM LR)
Externally driven collisions deformed magnet can assembly	Magnet can redesign, encapsulated magnets	Strengthened ass'y, increased mass	Neglible
Concern about debris in gas bearing system	Gas Bearing system inlet filter	Implemented	Neglible
Increased gas bearing margin for static acceleration loading	Implement displacer body gas bearings	Demonstrated	0.4W
Alternator rubs resulting from externally driven collisions and resulting deformation	Modified running clearance in alternator	Demonstrated	0.3W
Clearance seals	Studied correlation between clearance and output power	Correlated gap change with power change and simulation	Correlation established
ASC Test Bed (ATB)	**All Design mods listed above**	**Demonstrated**	**4W total loss**
Exported vibration	Cryocooler production active balancer (tailored)	Demonstrated vibration attenuation	Reduced exported vibration

Identified improvements to increase robustness and reliability were tested.
ATB demonstrated the ASC could still meet minimum product specification power requirement.

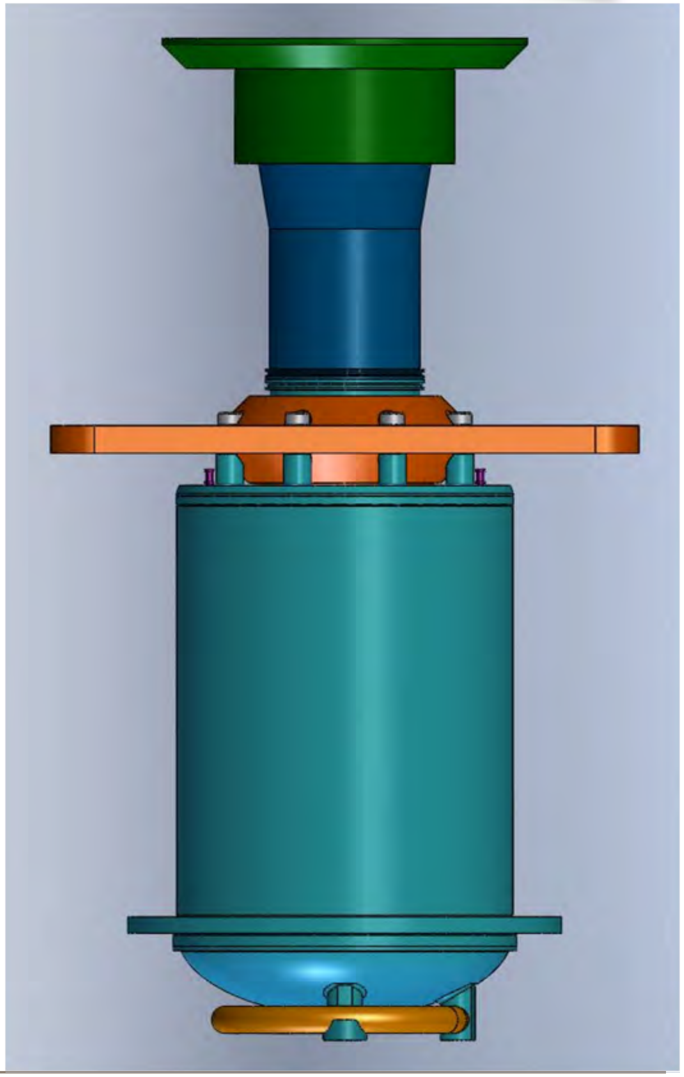
SRSC design overview

SRSC design improvements over ASC

- Shorter & larger alternator using encapsulated SmCo magnets
- Doubled running clearances in alternator
- Larger displacer rod – for required increased lateral load capacity
- Thickened engine cylinder with improved mounting
- Inner laminations on separate structure
- Gas bearing inlet filter
- Debris free regenerator

- Series gas bearing check-valves (adds redundancy)
- Piston-Displacer spring bumper (eliminates alternator toggle when stopped)

- Mechanical Piston Centering Spring
- Limit bumpers included in back end of machine



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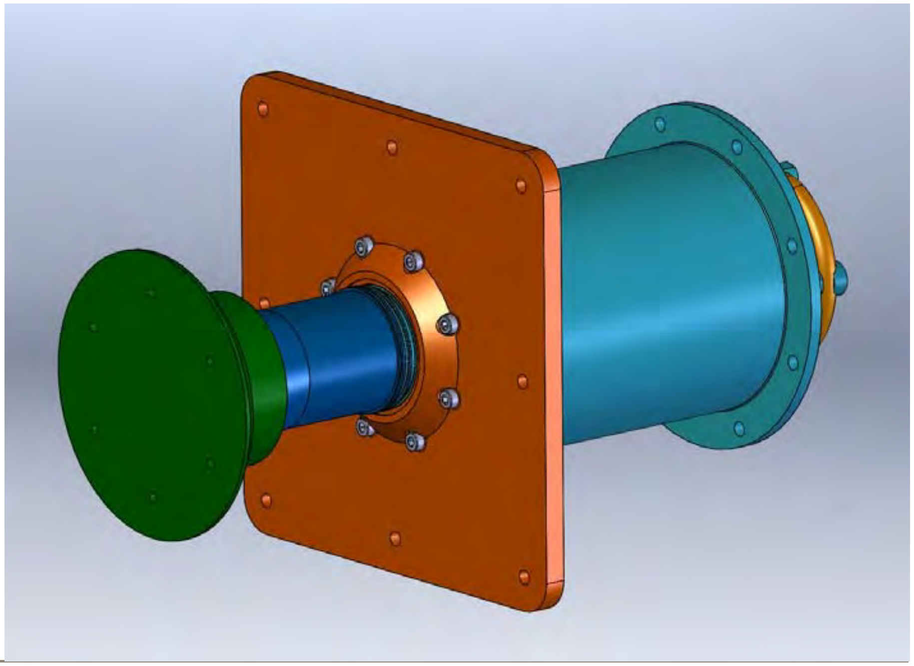
Size and Mass Estimate

- Mass estimate
  - *2.00 kg (convertor only, without CSAF and external acceptor)*
- Dimensions
  - *Length: 230 mm*
  - *OD, Pressure Vessel: 77 mm (without flange)*
  - *OD, Head interface: 84 mm (subject to generator design)*
  - *CSAF width: 135 mm (subject to generator design)*



Convertor Compliance With Requirements

Compliance Matrix, Requirements

Category	Requirement	Compliance
Design life	20 years of continuous operation at full power	Yes
Convertor power output	Enables a 200 to 500 W_e generator	Yes, 64W_e convertor size matches well with the 200 to 500 W_e generator size
Start-stop cycles	Capable of 150 start-stop cycles without any permanent effect on performance	Yes
Launch vibration	No permanent loss of power or long-term effect after exposure to launch acceptance vibration testing, defined as: • Duration of 1 min in each axis • Convertor operating at full power at onset of random vibration • Random vibration of magnitude 10.35 g_{rms} in all axes with following spectral distribution:	Yes

Frequency (Hz)	Acceleration Spectral Density (g^2/Hz)
20	0.015
50	0.100
250	0.100
300	0.080
800	0.080
2000	0.015

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Compliance Matrix, Requirements

Category	Requirement	Compliance
Static acceleration	Capable of exposure to the following static and quasi-static acceleration with no permanent effect on performance, while operating at full design piston amplitude: • 5 g for 5 days in all axes • 20 g for 1 minute in all axes	Yes
Thermal-to-electric conversion efficiency	≥ 24% when cycle rejection temperature is ≥100 C (Defined as electrical power out from the convertor divided by heat input to the convertor)	Yes, 29.2%
Partial power operation	Maintains ≥ 20 % thermal-to-electric conversion efficiency when input thermal power is 50% of designed maximum	Yes, 25.7%
Hot-end operating temperature	< 1000 °C	Yes, 720° C
Cold-end operating temperature	• Requires no less than 100 °C to meet efficiency goal Capable of operation between 20 and 175 °C without any permanent effect on performance	Yes

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Compliance Matrix, Requirements

Category	Requirement	Compliance
Thermal energy input	Designed to accept heat from an integer number of GPHS-Step 2 modules (250 ± 6 W_{th} each)	Yes
Atmospheric environment	Capable of operation in the following environments without any permanent effect on performance: • Earth : 1 atm of air • 2 atm of argon • Deep space : vacuum • Mars : 5 torr CO_2 Titan : 1.5 atm 94-99% N_2, 1-6% CH_4, and 0.2% H_2	Yes
Tolerance of loss of electrical load	Capable of loss of electrical load at the alternator terminals for 10 seconds while operating at full power, without any permanent effect on performance	Yes
Transmitted forces	Enables a generator that reduces transmitted forces to the spacecraft to less than 10 N	Yes, unbalanced force of a single convertor is ~270N. This can be balanced with opposing convertors.
Specific power (W/kg)	> 20 W/kg (convertor only)	32.6 W/kg convertor only

Compliance Matrix, Requirements

Category	Requirement	Compliance
Size	Enables a generator design that will fit in the DOE shipping container of the following dimensions: • 86 cm diameter 144 cm height	Yes
Performance measurement	The convertor design shall enable direct measurement of the following items for performance testing: • Temperature of the interface to the heat source • Temperature of the interface to the heat rejection system • Alternator output (voltage, current, power, frequency) • Piston motion • Displacer motion Disassembly for internal inspection	Yes, • Thermocouple wells in external acceptor for heat source temperature • Thermocouple wells in CSAF for heat reject temperature • Alternator output can be measured at feedthroughs • FLDT's used for piston and displacer motion measurement during testing

Compliance Matrix, Goals

Category	Goal	Compliance
Performance degradation	Output power decreases by less than 0.5 % per year for the case of constant thermal input (Does not include generator-level sources of degradation, such as Pu-238 fuel decay, or insulation degradation)	Yes
Thermal-to-electric conversion efficiency	≥28% when cycle rejection temperature is ≥100 C (Defined as electrical power out from the convertor divided by heat input to the convertor)	Yes, 29.2%
Radiation	No loss of performance after exposure to 300 krad	Yes
EMI	DC magnetic field : less than 100 nT at 1 m while operating at maximum power (No element of the design precludes characterization of the AC magnetic field)	ASC testing shows .11mT at 7 cm. Further testing would need to be done at 1 m.
Autonomy	• No operational adjustments needed during launch No adjustments needed during static acceleration	Yes
Manufacturability	Utilizes proven and effective manufacturing approaches	Design largely based on ASC
Instrumentation necessary for flight convertor operation	Enables a generator that performs long-life science missions without the need for long-life sensors on the convertor(s)	There are no requirements for sensing, Sunpower has demonstrated open loop control

Predicted Performance

- Convertor exceeds all performance requirements and goals

	Head Temp (C)	Reject Temp (C)	Heat In (W_{th})	Output Power (W_e)	Efficiency (%)	Efficiency Req, (Goal) (%)	Specific Power (W_e/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

Convertor Trade Studies

Convertor Power Level Trade Study

Convertor Power Level Trade Study Objectives

- Select optimum convertor size to address potential generators in the 200 W to 500 W range
- Major considerations:
  - *Heat source with 4 to 8 GPHS modules*
  - *Convertor with sizes selected to integrate well with integer GPHS modules*
  - *Power output / efficiency as a function of convertor size*
  - *Mass of power conversion system*
  - *Ability to add redundant convertor pairs – generator reliability*

Goal is to select a convertor size that will provide flexibility in developing future generator integration concepts across the generator power range from 200 W to 500 W

Convertor Size
First Order Mapping to Integer GPHS Module Increments

Number of GPHS Modules	GPHS Thermal Inventory	Gen Thermal Efficiency	Input Thermal Power, Wt	Convertor Design Thermal Load, Wt — Number of Operationg Convertors Required: 2	4	6	8	10	12	14	16	Generator Power, We
2	250	0.86	430	215	108	72	54	43	36	31	27	127
3	250	0.86	645	323	161	108	81	65	54	46	40	191
4	250	0.86	860	430	215	143	108	86	72	61	54	255
5	250	0.86	1075	538	269	179	134	108	90	77	67	319
6	250	0.86	1290	645	323	215	161	129	108	92	81	382
7	250	0.86	1505	753	376	251	188	151	125	108	94	446
8	250	0.86	1720	860	430	287	215	172	143	123	108	510

Number of GPHS Modules	GPHS Thermal Inventory	Gen Thermal Efficiency	Input Thermal Power, Wt	Convertor Size, We — Number of Operating Convertors Required: 2	4	6	8	10	12	14	16	Generator Power, We
2	250	0.86	430	64	32	21	16	13	11	9	8	127
3	250	0.86	645	96	48	32	24	19	16	14	12	191
4	250	0.86	860	127	64	42	32	25	21	18	16	255
5	250	0.86	1075	159	80	53	40	32	27	23	20	319
6	250	0.86	1290	191	96	64	48	38	32	27	24	382
7	250	0.86	1505	223	111	74	56	45	37	32	28	446
8	250	0.86	1720	255	127	85	64	51	42	36	32	510

The 64 W and 32 W convertor size align well with the integer number of GPHS modules across the generator power range from 200 W – 500 W

Generator Size - Recommendation

- Addition of a single redundant convertor pair can significantly enhance the generator reliability
- Although the larger convertor sizes (127 W, 96 W) have higher efficiency and specific power, incorporating a redundant convertor pair adds a larger increment of mass to the generator
- Larger convertors (127 W, 96 W) are less optimal for the 4-GPHS system
- The smaller convertor sizes (32 W, 64 W) better address the full generator power range
- The 64 W generator has higher performance (efficiency and specific power) providing a generator that provides more power for a given number of GPHS modules
- The 64 W convertor size is recommended to address generator power levels in the 200 W to 500 W range

64 W convertor chosen as baseline for SRSC.

Convertor heater head material

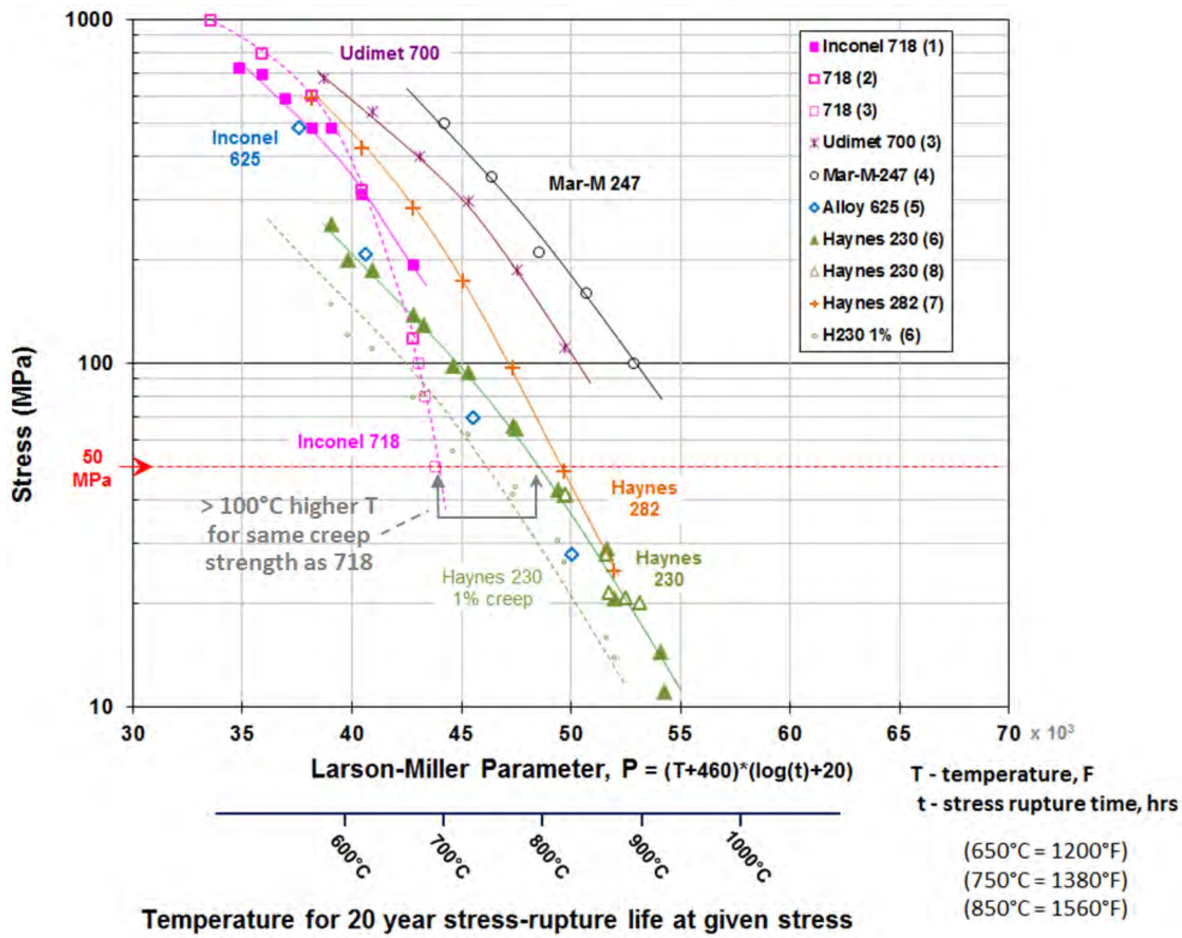
Heater Head Candidate Alloy Requirements

Requirements

- Creep strength improvement over Inconel 718
- Creep strength enabling 20-year life
- Large creep database available; readily commercially available; forming, machining and joining knowledge available
- Wrought bar commercially available at heater-head sizes
- Capable of necessary welding, brazing, diffusion bonding (for acceptor HEX, hot shoe, convertor sealing)
- Creep strength maintained after joining thermal processes

Candidate Alloy Creep Strength

- Haynes 230 offers ~100°C gain in capability over Inconel 718



(650°C = 1200°F)
(750°C = 1380°F)
(850°C = 1560°F)

Haynes 230 Machining, Welding and Brazing

Machining - HAYNES® 230® alloy is similar in machining characteristics to other solid-solution-strengthened nickel-base alloys... ...can be machined using conventional methods at satisfactory rates. (ref. 6)

Welding - Relatively weldable, compared to other high-creep-strength nickel-base superalloy. Weldability challenges are not anticipated for heater-head welds that are relatively small, unrestrained, not heavily loaded, and that operate at relatively low temperature.

Brazing - No unique braze issues. Brazing is a function of joint design, function, required quality of the joint, braze alloy selection, surface preparation, etc. For some of the joints, nickel plating may be advisable to assure the best wetting and braze alloy flow.

Displacer gas bearings

Increased Displacer Gas Bearings

Trade: If half power operation and static acceleration loading become concurrent requirements, there is a need for stronger displacer bearings.

- Option: Increase displacer rod diameter
- Option: Add displacer body gas bearings
  - *Larger diameter allows for stronger bearings than the rod is capable of*
  - *Body bearings will complement rod bearings*
  - *Adds new complexity to the design*

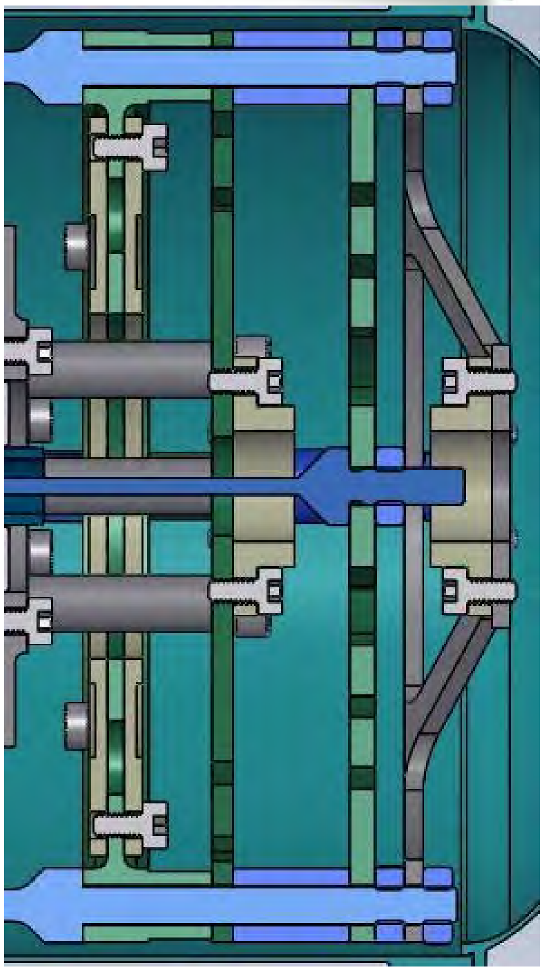
Displacer Rod Diameter increased in baseline SRSC design

Piston centering

Piston Centering Methods

Trade: Means of centering the piston for startup

- Option 1: Mechanical centering with piston beams added to displacer spring (Sunpower patent)
- Option 2: Magnetic centering
- Option 3: Separate piston mechanical spring
  - *Benefits*
    - Avoids undesired piston vibration modes
    - More capability for adding spring to the piston, compared to the combination spring
    - Integrates well with bumper layout
    - Will use established cryocooler production method for assembly
    - Gas bearing lateral stiffness is much greater than mechanical spring lateral stiffness

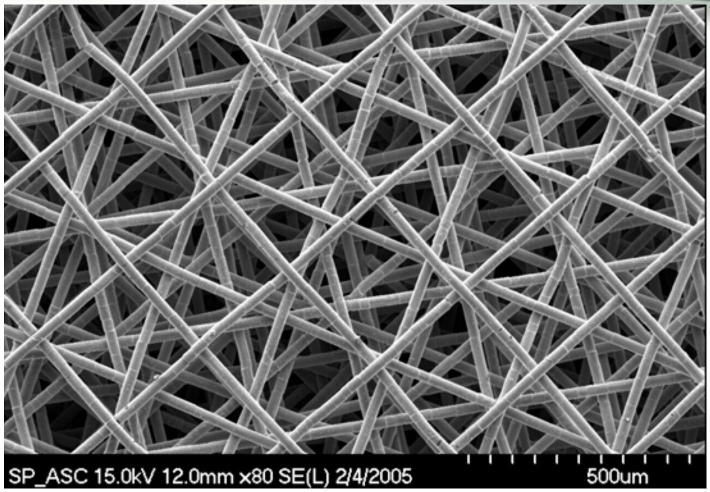


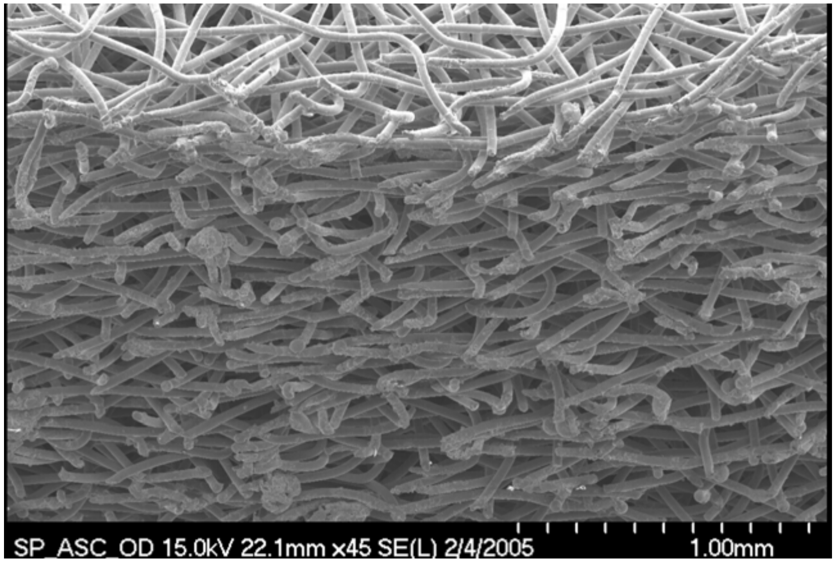
Final Configuration: Separate piston mechanical spring

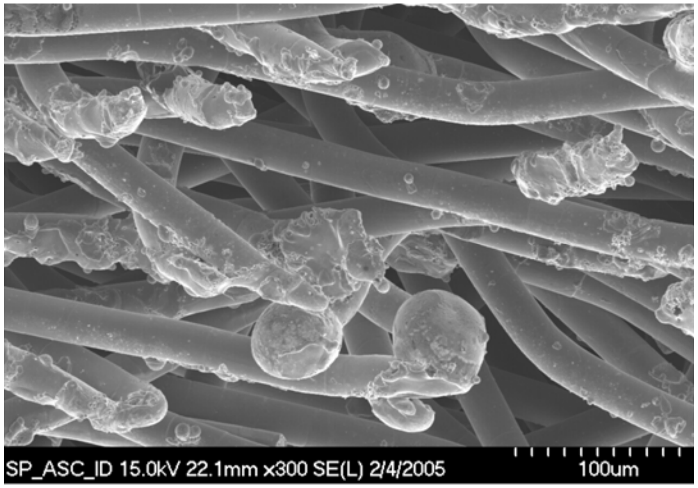
Regenerator

Regenerator

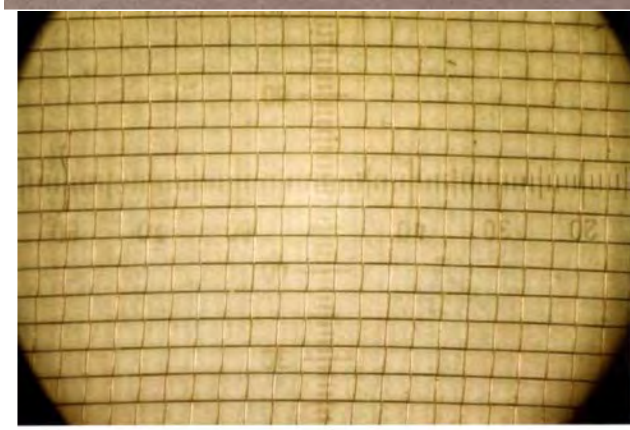
Primary cause of debris in the past is due to wire cutting slag seen in lower pictures

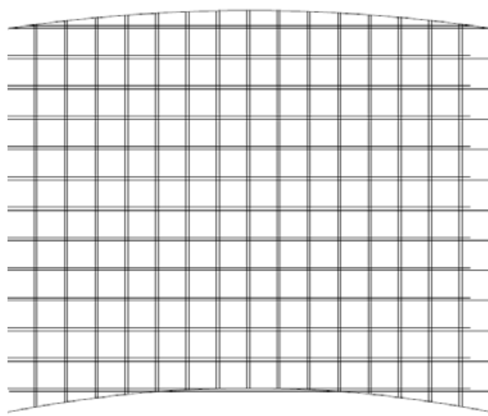


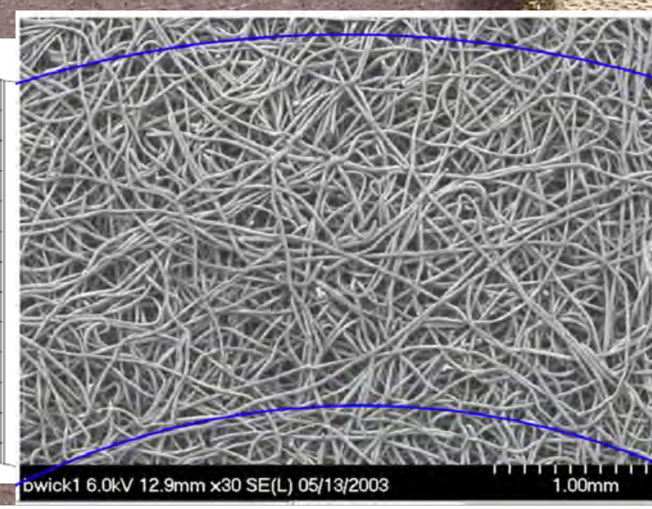




Regenerator







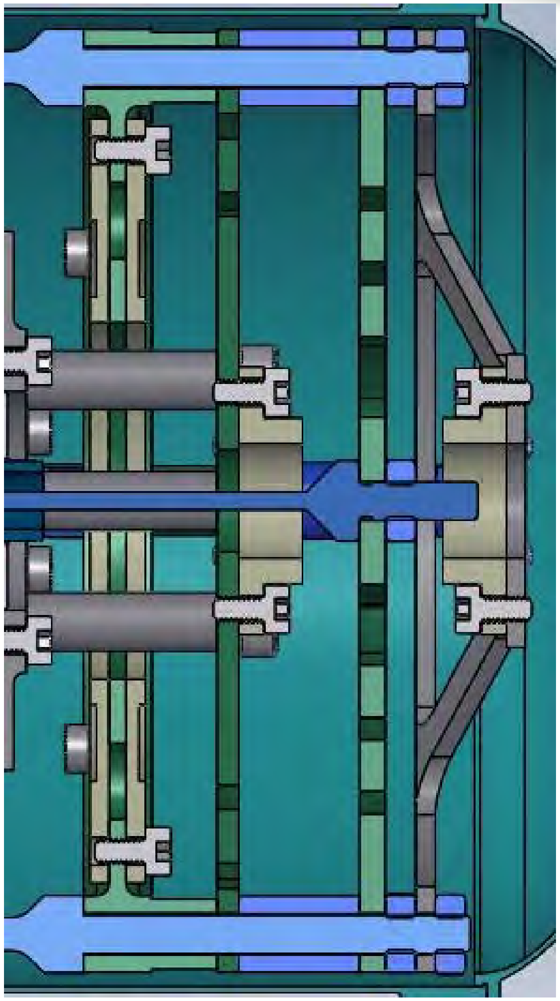
Regenerator ranking

- Eight options were considered for the SRSC regenerator, including:
  - Loose pack and sintered
  - Bekaert short fiber technology
  - Others
- Final Selection: Use current Sunpower cryocooler regenerator production methods
  - Eliminates slag
  - Process has been in use for ~15 years
  - SRSC may use an additional cleaning process

Unloaded Operation Tolerance

Bumper Design

- Bumpers are included in the back end of the machine to protect the convertor in an overstroke condition
- Separating the bumpers from the other converter components keeps any local deformation due to impact away from the critical running surfaces
- There are four contact faces:
  - *Piston to ground, in direction*
  - *Piston to ground, out direction*
  - *Displacer to ground, out direction*
  - *Piston out, relative to displacer*
- Brass will be used as the contact surfaces for the stops

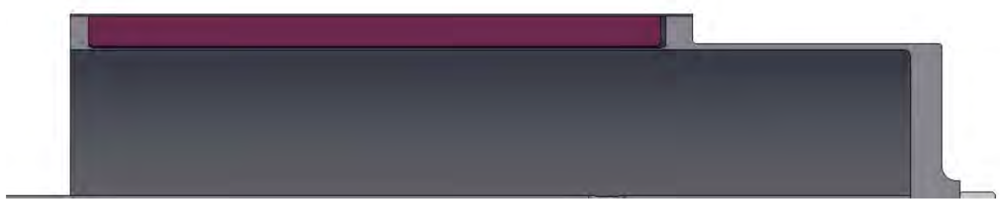


Bumpers incorporated into SRSC design for loss of load operation and protection against overstroke.

Convertor Design Details

Magnet Can Encapsulation

- There is concern that the magnets can be damaged during unintentional impact due to their brittleness
- Magnet design details for SRSC:
  - *Full height ribs to the can at both ends of the magnets*
  - *Welded titanium sleeve to the OD to fully encapsulate the magnets*
  - *The sleeve will be stitch welded in few places for venting during charging of the convertor*
  - *Wall thicker in the area not under the magnets*



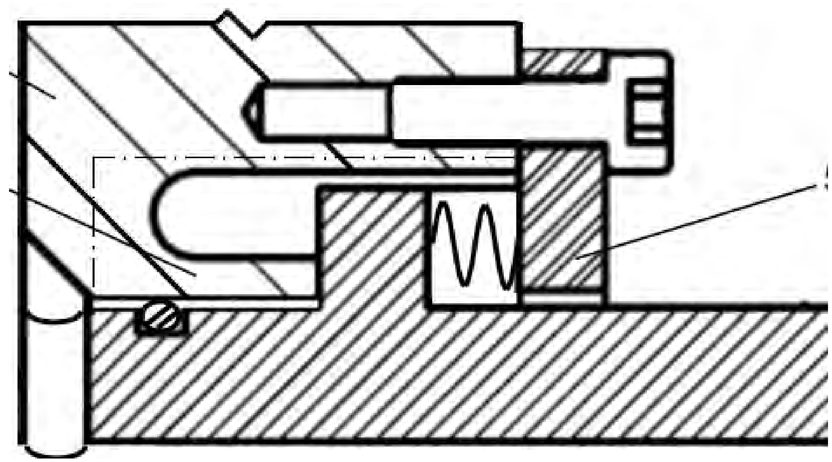
Method was developed, reduced to practice, and tested in the ASC-E3 Technology Assessment task.

Redundant Check Valves

- The SRSC will use redundant, series check valves to eliminate the single point failure mode of a single check valve
- Design also includes a filter as an additional layer of protection
- The series check-valve idea was introduced in the past. Implementation for SRSC was developed during Phase 1
- Fits within the existing space available
- The first check valve charges an intermediate storage volume, which then charges the gas bearing reservoir through the second check valve

Cylinder Mounting

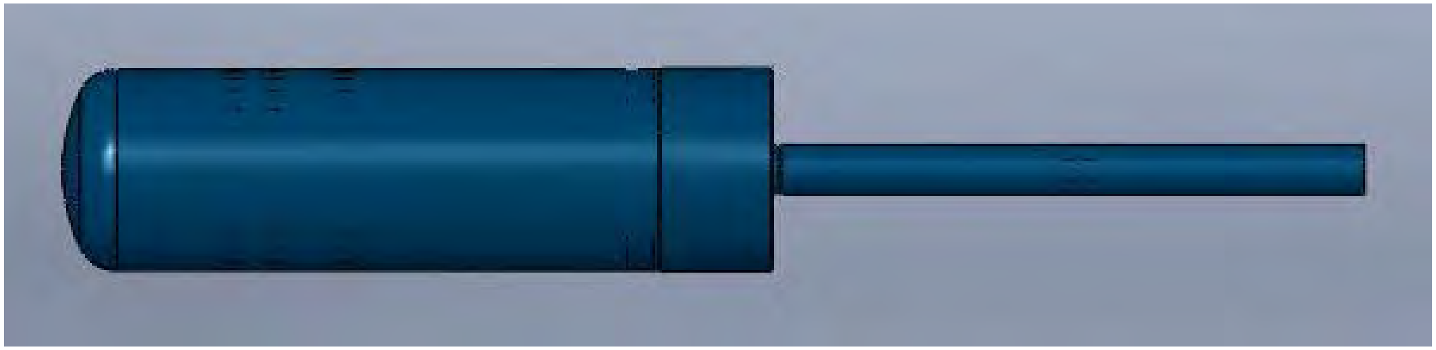
- Cylinder mounting method implemented for SRSC is designed to improve the isolation of the cylinder from the transition
- A groove is added to the transition to create a thin wall section for the cylinder clamp face
- A wave spring is used on the back face of the cylinder rib to provide the preload against the clamp face
- The wave spring is captured and preloaded with a clamp ring
- Bolt torque does not have an effect on the cylinder
- Sunpower patent pending (at right)



Method was demonstrated successfully in a commercial engine project.

Displacer Material

- Haynes 230 was also chosen as the SRSC displacer material
- Driven by the desire to weld the dome to body instead of brazing, which will allow displacer body gas bearings if necessary
- Displacer venting accomplished through two radial drilled holes in the rod



Convertor Analysis

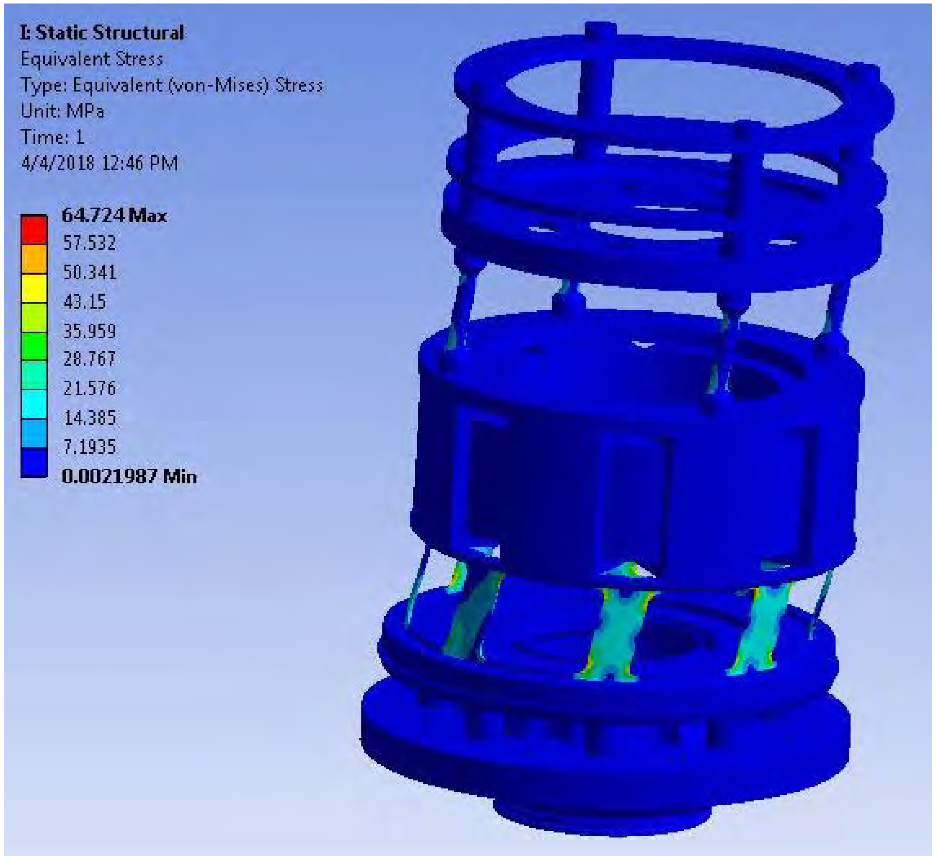
Static Acceleration

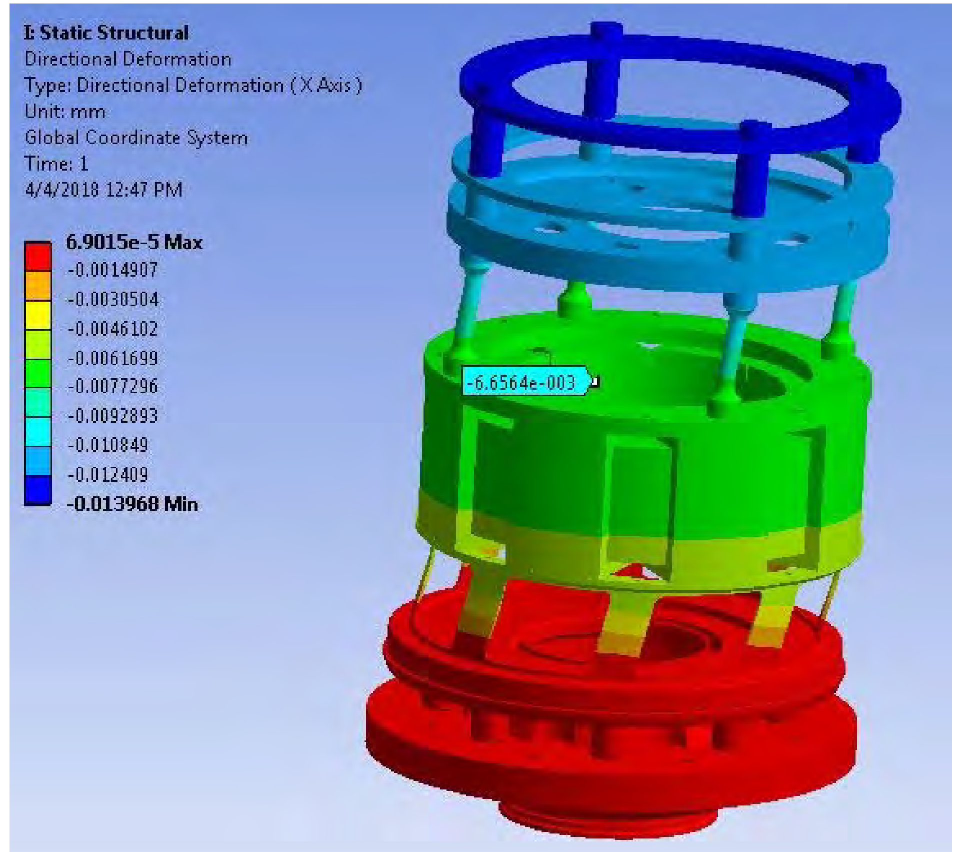
Static Acceleration Compliance

- Requirements, at full power, in all directions
  - *5 g for 5 days*
  - *20 g for 1 minute*
- Also desired to support static loads at part power to accommodate operating redundant convertors
- Analysis done for SRSC
  - *Structural analysis of stator and spring standoff assembly*
  - *Structural analysis of cylinder mounting*
  - *Piston gas bearing analysis*
  - *Displacer gas bearing analysis*

Static Acceleration Compliance

- Stator and spring standoff assembly were analyzed under 20g lateral load

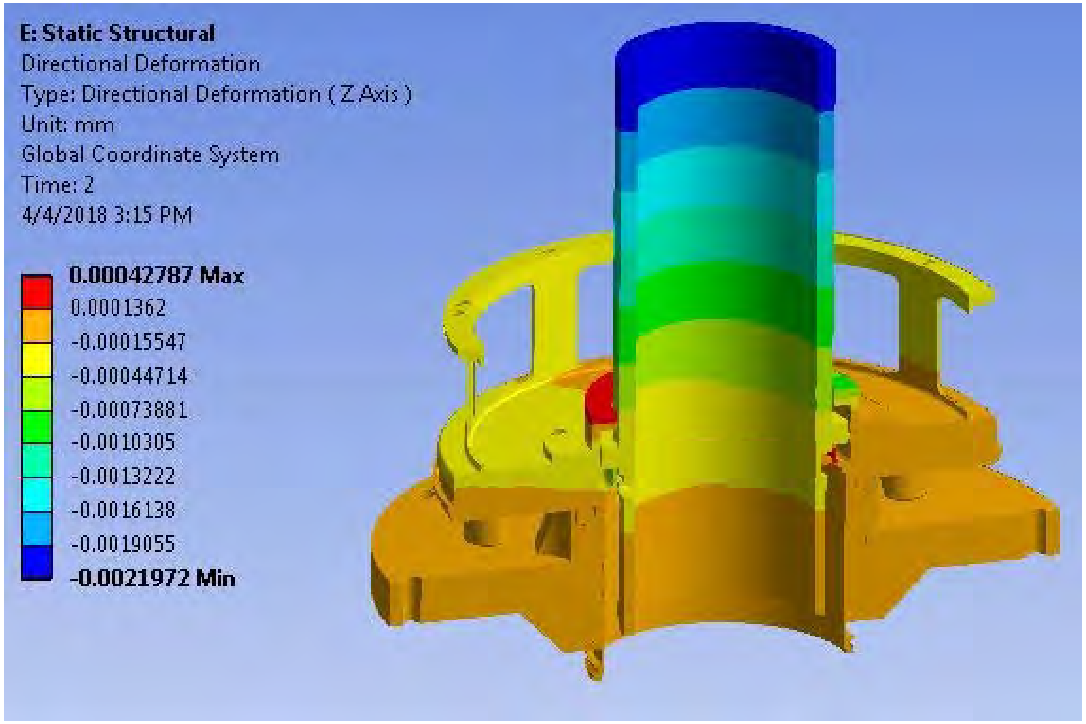




- Transition: MS 11 to yield, Spring Standoff: MS 35 to yield
- Radial movement of 7 µm does not affect alternator operation

Static Acceleration Compliance

- Cylinder was analyzed under 20 g lateral load
- Model included point masses representing the piston and displacer



- Cylinder shows minimal lateral movement
- Cylinder clamp spring maintains preload
  - *Minimum preload is 366N, Lateral load is 58N*

Static Acceleration Compliance

- Gas bearing capacity depends on the operating condition of the convertor

- Displacer rod Capacity at full power
  - Nominal: 7.9 g
  - Minimum: 5.4 g
- Displacer rod Capacity at 2/3 power
  - Nominal: 5.9 g
  - Minimum: 4.0 g
- Piston Capacity at full power
  - Nominal: 41.4 g
  - Minimum: 22.5 g
- Piston Capacity at 1/2 power
  - Nominal: 24.7 g
  - Minimum: 9.4 g

Static Acceleration Compliance

- Lateral 5g load
  - *Piston and displacer are capable of supporting at full power*
  - *Piston is capable of supporting at half power*
  - *Displacer is capable of supporting at 2/3 power*
  - *Displacer capability can be increased with displacer body bearings if lateral load requirement is overlapped with partial power requirement (is not currently)*
- Lateral 20g load
  - *No structural issues with the converter*
  - *Piston is capable of supporting at full power*
  - *Displacer rod will not support but the short duration can be accommodated by the xylan*
    - Size so that displacer body is the first place to contact to increase wear area

SRSC meets current requirements
Displacer body bearings are needed if static acceleration and half power operation requirements are modified to be concurrent.

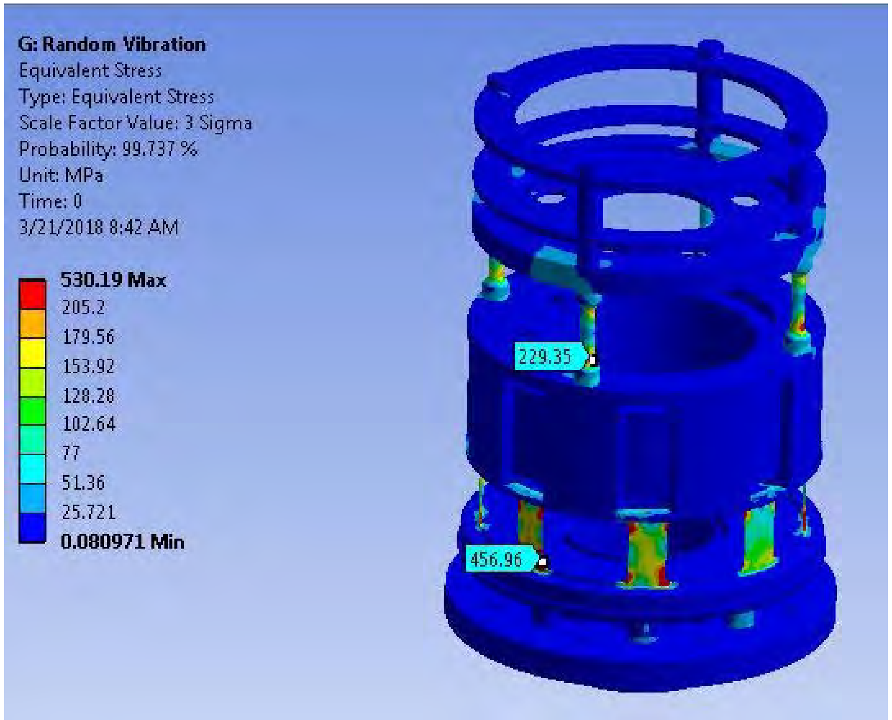
Launch Loads

Launch Loads Compliance

- SRSC Requirements
  - *10.35 g_{rms} in all directions*
  - *Convertor operating at full power*
- ASC Background
  - *Acceptance testing performed at 14.8 g_{rms} axial and 7.3 g_{rms} lateral*
- Analysis done for SRSC
  - *Structural analysis of stator and spring standoff assembly*
  - *Structural analysis of cylinder mounting*

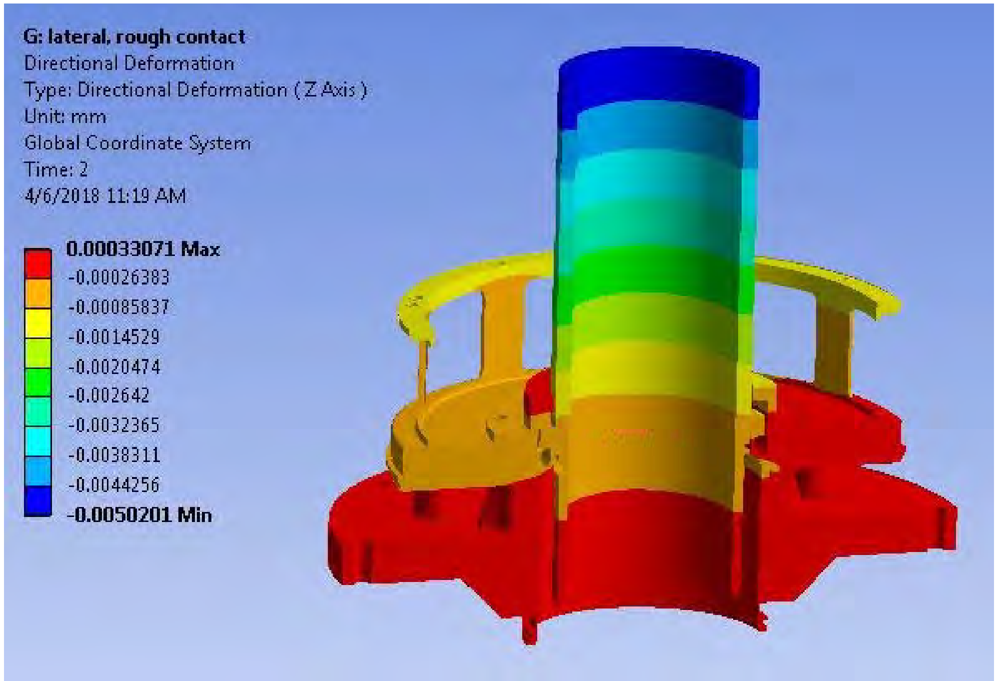
Launch Loads Compliance

- FEA analysis was performed on the transition, stator, and spring standoff assembly
- Highest stresses are in the transition standoffs and spring standoffs
  - *Transition:*
    - MS 0.71 to yield
  - *Spring Standoff:*
    - MS 1.38 to yield



Launch Loads Compliance

- Random vibration analysis cannot model non-linear sliding contact at the cylinder mount flange.
- Static lateral acceleration analysis was redone with an increased acceleration to replicate the random vibration deformation, required ~45 g
  – *This allowed the preload spring and non-linear contact to be modeled*
- Cylinder clamp still maintains preload
- Lateral load applies a moment of 2.7 Nm to the cylinder clamp joint
  – *MS 2.1 to separation due to tilting*



Thermal Loads

Cold End Operating Temperature Compliance

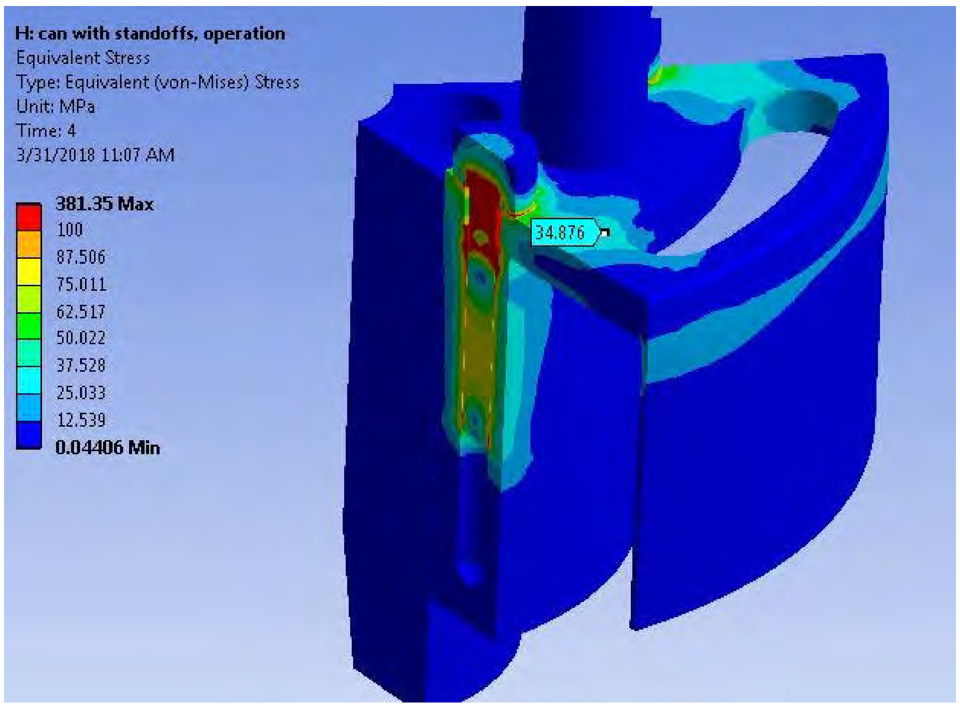
Two effects of 175 °C reject operation were considered. Analysis was performed at 200 °C to allow for the backend temperature being above reject temperature.

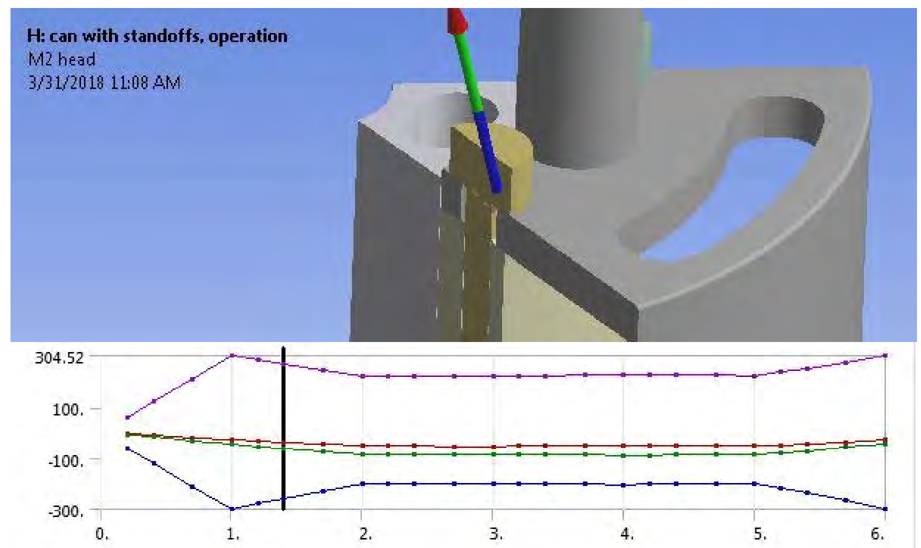
- Base material degradation
  - *Mostly organics*
  - *Magnet demagnetization*
- Bolted Joints / part CTE differences
  - *Magnet Can to Piston Joint*
  - *CSAF to Transition Joint*
  - *Spring Standoff bolts*
  - *Cylinder Mount*
  - *Stator Assemblies*

- A full convertor thermal-structural FEA was run and showed no other issues

Piston to Magnet Can Joint

- Magnet can alternating stress during operation is 35 MPa
  - *Analysis performed at 5 mm piston amplitude*
  - *125 MPa fatigue allowable*
- Bolts maintain preload at high reject
  - *Minimum per bolt preload is 600 N, drops to 400 N at high reject*
  - *Per bolt load <30 N*



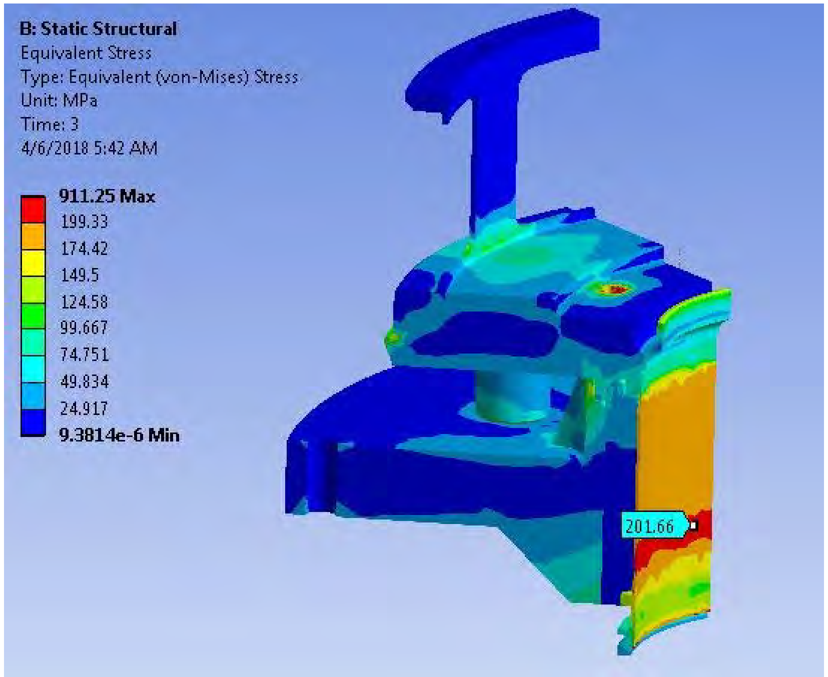


Transition and Pressure Vessel

Structural analysis was done to verify integrity of the new design

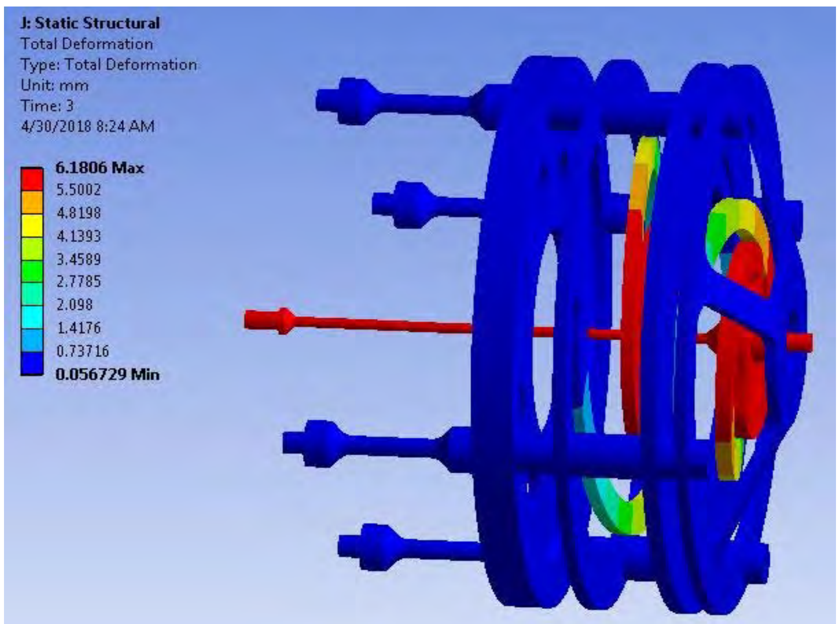
- Pressure Vessel, Hand Calculations:
  - *Highest pressure is 4.7 MPa (at 200 C backend temperature), design wall thickness: 0.5 mm*
  - *ASME PV code minimum wall: 0.38 mm*
  - *NASA 5001: MS 1.04 to yield*

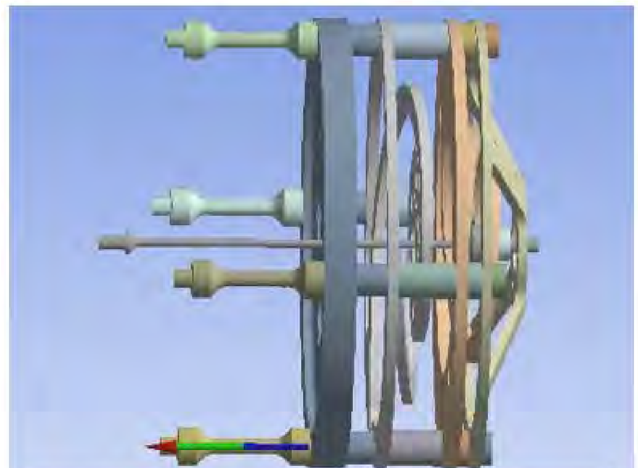
- Transition, FEA:
  - *Highest stress is in thin wall brazed area (201 MPa, MS 2.8 to yield)*
    - This stress was also present in the ASC design
  - *Artificial stress concentration at bolt joint causes the maximum stress in the plot*
  - *Stress in other locations is well below allowable*



Spring Standoff Assembly

- Spring standoff assembly was analyzed to evaluated the spring clamp bolts
- A thermal load of 200 °C was applied to the entire model
- Maximum piston and displacer amplitude, along with impact forces, was applied
  - *This is very conservative, these loads do not occur simultaneously in the convertor*
  - *MS to separation of 2*





Tabular Data

	Time [s]	Force Reaction 4 (X) [N]	Force Reaction 4 (Total) [N]
1	1.	-2000.	2000.
2	2.	-1902.4	1902.4
3	3.	-1338.	1338.
4	4.	-1902.4	1902.4
5	5.	-2000.	2000.

Load Steps:
1. Bolt Pretension Applied
2. Thermal Load Applied
3. Structural Loads Applied
4. Structural Loads Removed
5. Thermal Load Removed

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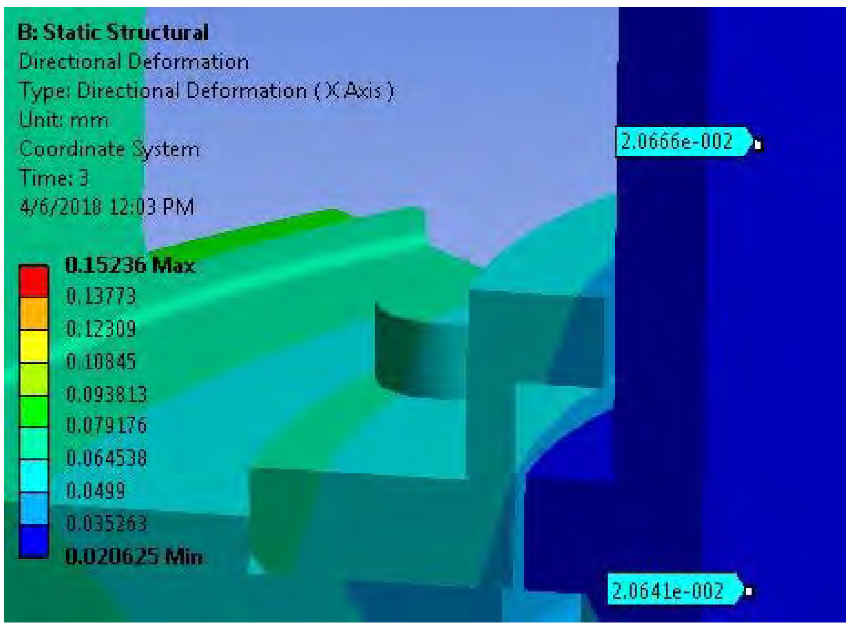
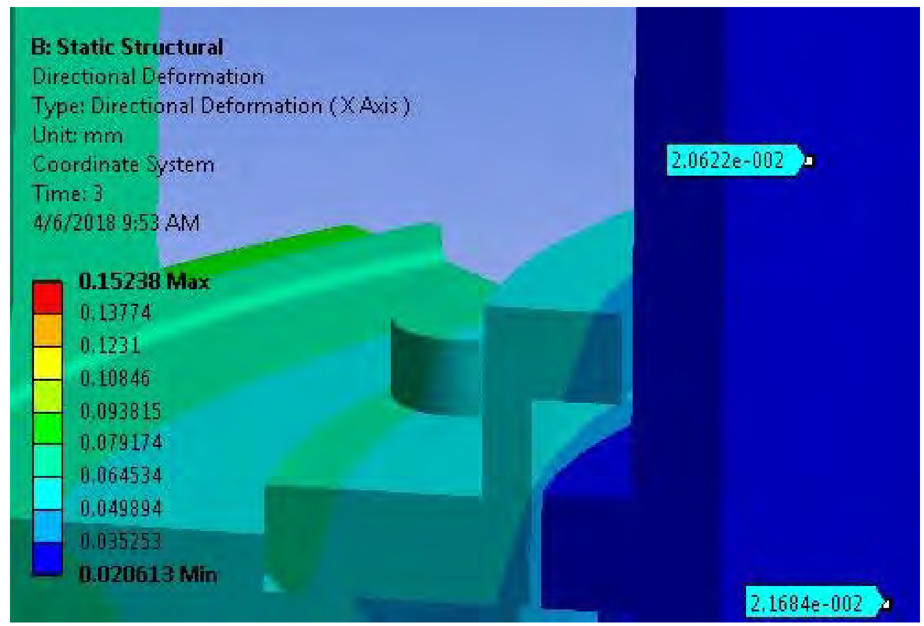
Cylinder Mounting Analysis

- FEA analysis of the cylinder was run to evaluate the cylinder mounting with pressure and thermal loads
- Plots show radial deformation of parts
- Analysis was run with frictional contact between the cylinder and transition (Left) and non-sliding contact (Right)
- Sunpower patent pending

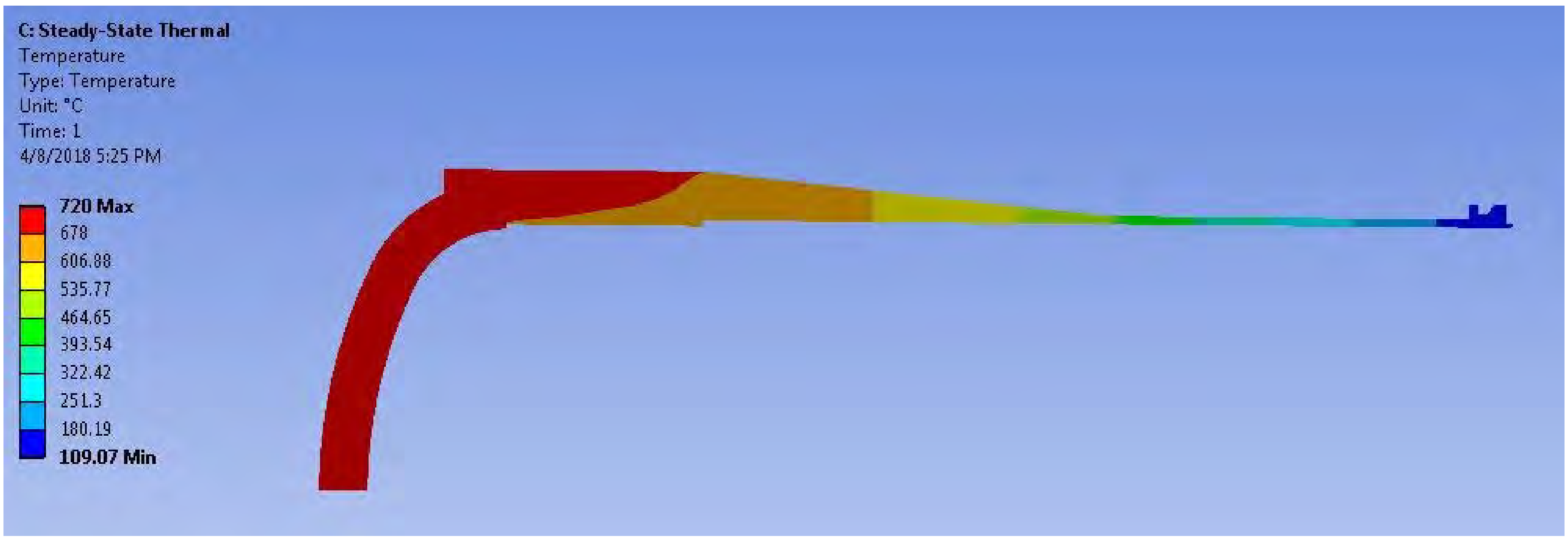




Cylinder meets reject temperature requirements.

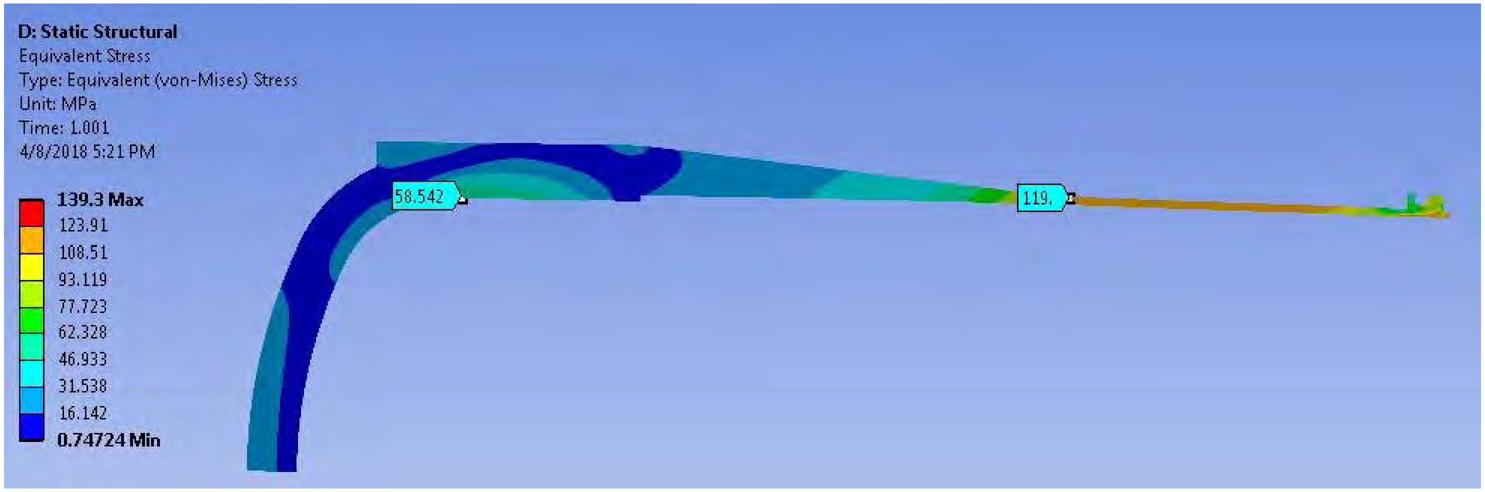
Heater Head Creep Analysis

- A 2D FEA of the heater head was performed to evaluate the head for creep life
  - *Thermal profile input from Sage analysis*
  - *Exponential form creep material model generated from creep data collected by Aerojet Rocketdyne*

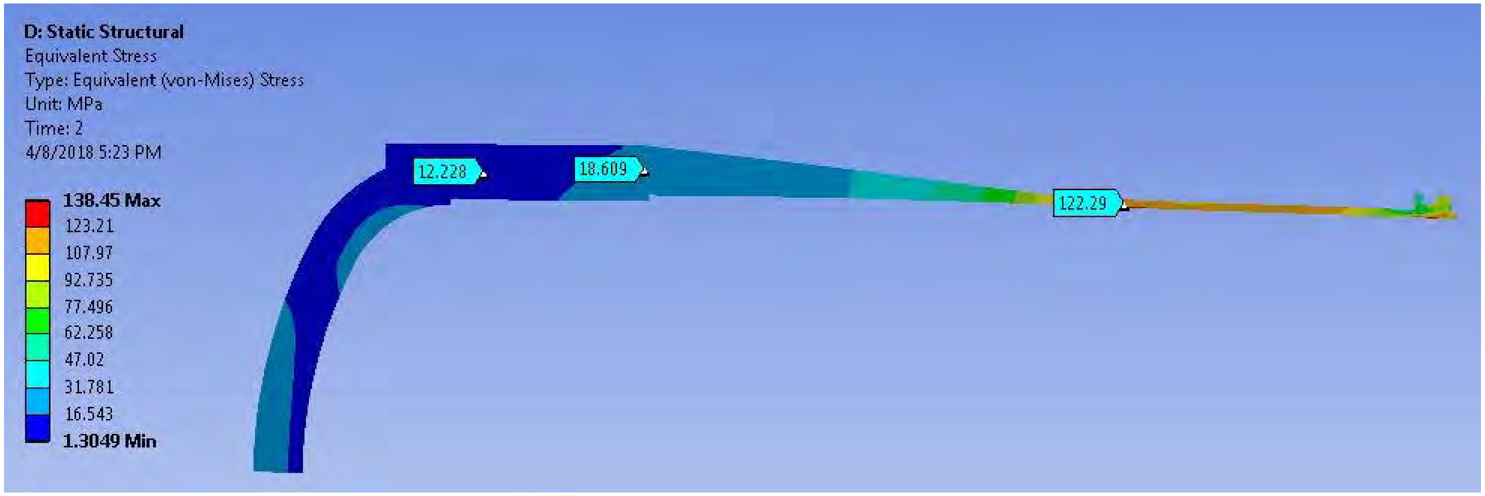


Heater Head Creep Analysis

- Stress at Beginning of Mission



- Stress at End of Mission



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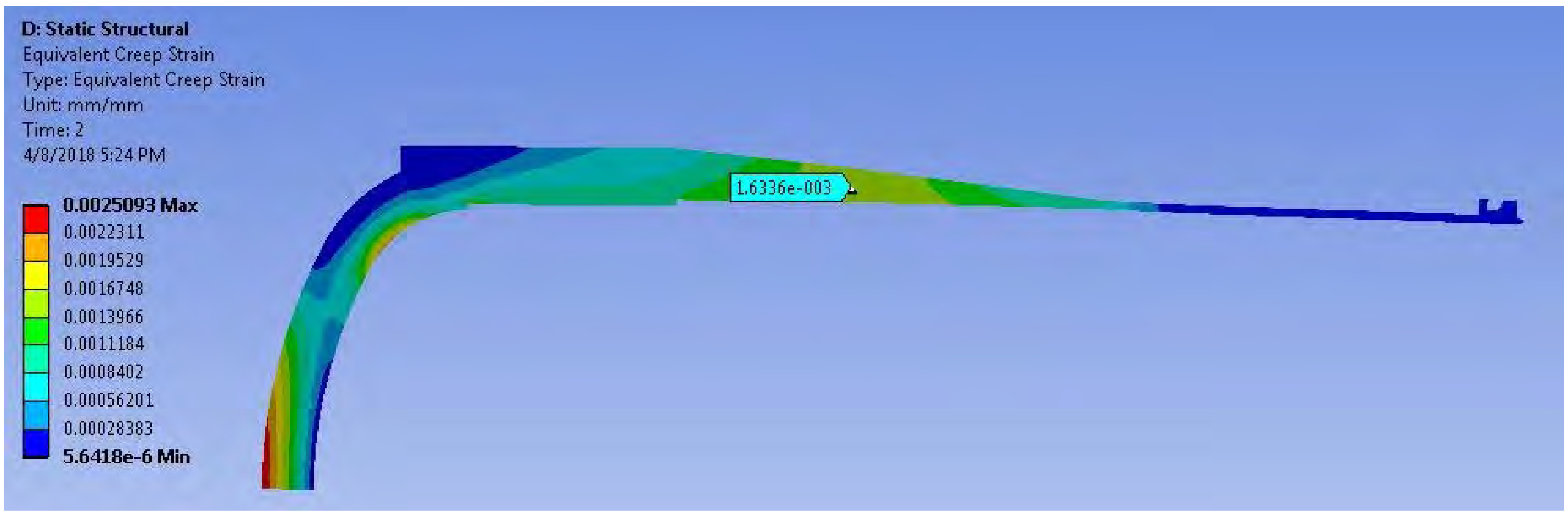
Heater Head Creep Analysis

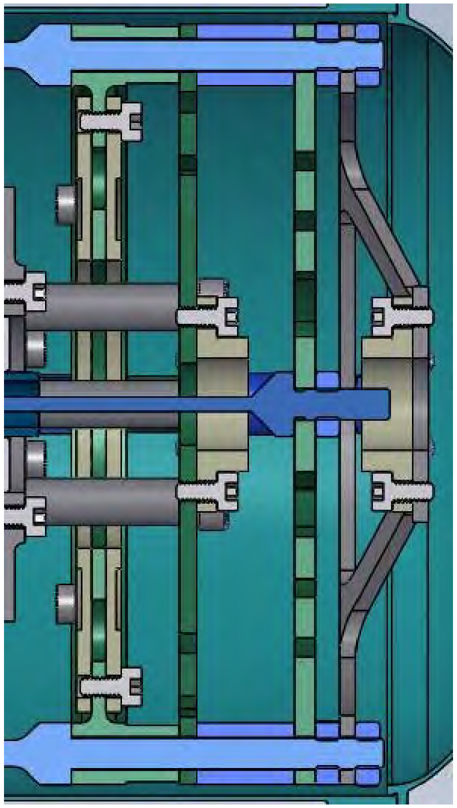
- Maximum creep is 0.25% in the dome region. 0.16% creep at the regenerator wall.
- Roughly 4 µm radial creep of head in the acceptor region, which is acceptable



Unloaded Operation

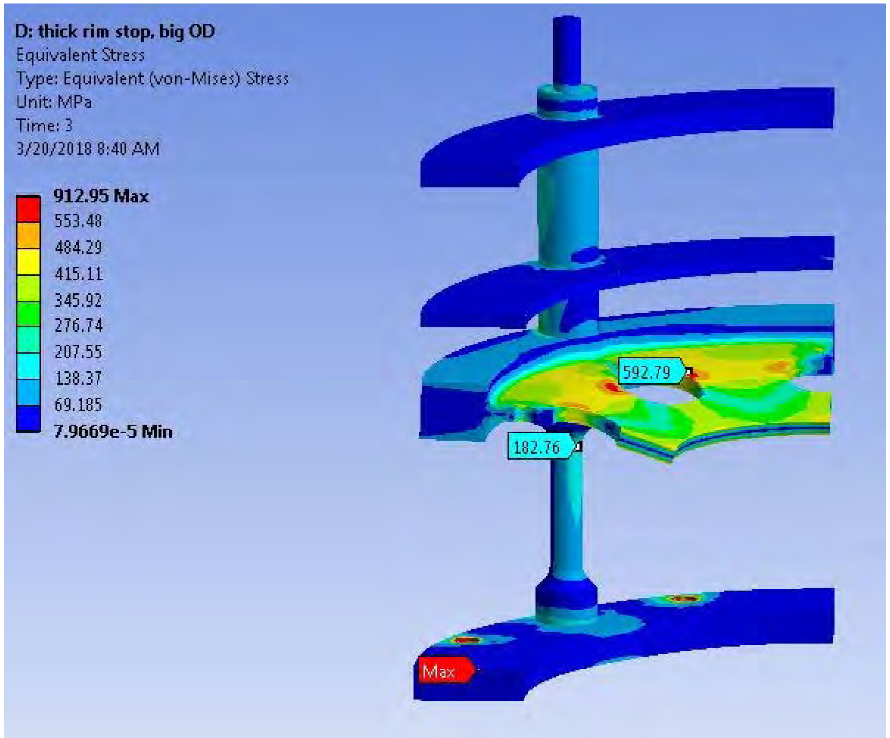
Unloaded Operation Compliance

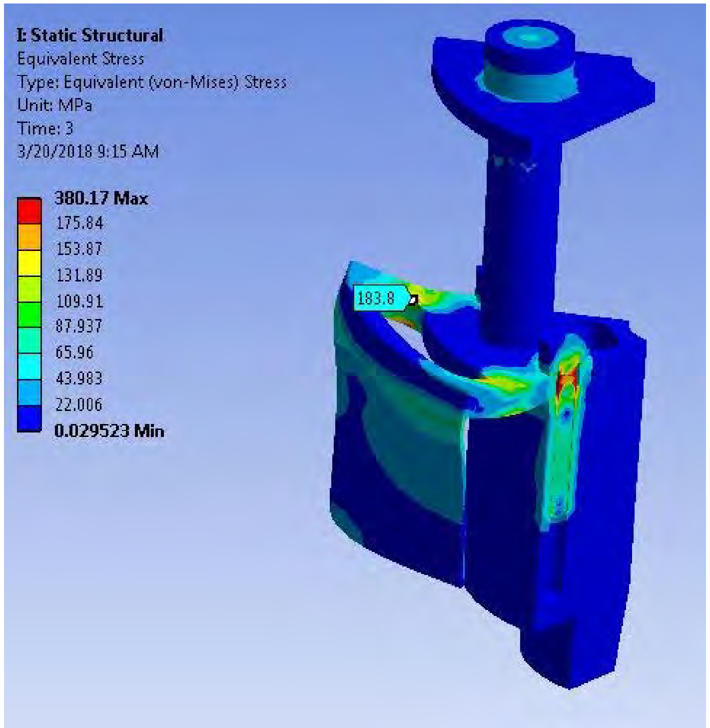
- Bumpers prevent damage to the hitting components but do not absorb all of the cycle energy
- As a starting point, the bumpers were designed as springs to accommodate an impact energy of ½ of a cycle at 80W
- Energy balance during unloaded operation:
  - *Displacer phase angle drops*
  - *Increased pumping losses*
  - *Sound noise*
  - *Surface yielding of impact components*
  - *Damping in bumper structure*



Unloaded Operation Compliance

- Spring standoff FEA results using 0.4 J impact energy
  - *Stop Plate: MS .35 to yield*
  - *Spring Standoff: MS 2.0 to yield*
  - *Magnet Can: MS 1.3 to yield*
  - *Stop plate deflection: 0.5 mm*





Initial Generator Layout Concepts

Key Requirements

Design Life: 20 years

Power Output: 200 W to 500 W

Launch Vibration: 0.1 g^2/Hz (10.35 grms) / +3dB for qualification

Static Acceleration: - 5 g x 5 days in all axes while operating at full power at onset
- 20 g x 1 min in all axes while operating at full power at onset

Thermal Efficiency: Maximize generator thermal performance

Partial power operation: - Convertor > 20% with 50% thermal input
- Evaluate generator concepts up to 100% redundancy

Hot-end temperature: GPHS surface temperature: 700°C < Tsurface < 1100°C

Cold-end temperature: Goal to keep converter <175°C during VGA

Thermal energy input: Integer number of bricks

Atmosphere: - Operate in vacuum and atmospheric environments;
- Earth, 2atm Argon, deep space, Mars, Titan

Transmitted forces: Low Transmitted forces

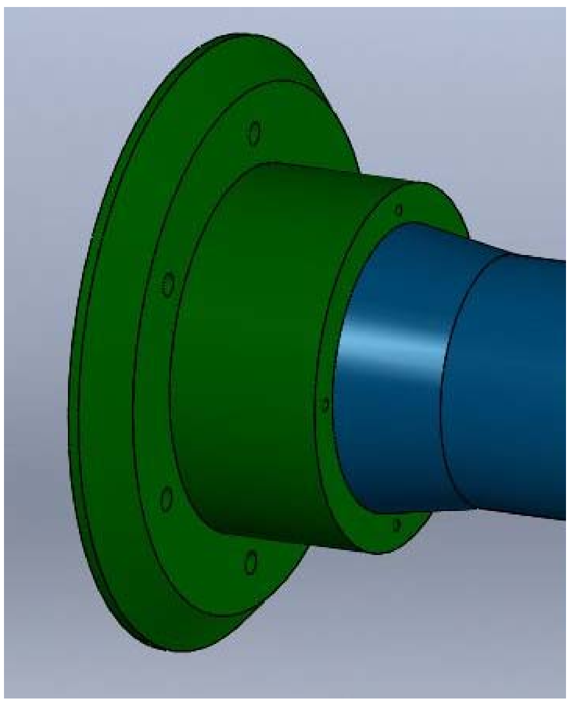
Size and Volume: Generator fits within 9904 shipping container

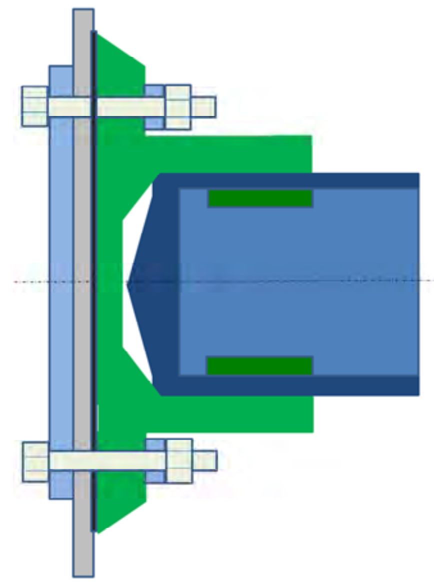
Desired Features

- Ability to scale in the 200W to 500W power range - consider heat sources with 3 to 8 GPHS modules
- Ability to incorporate redundancy in power convertor pairs
- Shared heat input – ability to distribute heat from the GPHS modules to neighboring convertor pairs in the event of a failed convertor pair
- Shared heat rejection – ability to distribute/spread heat over the heat rejection surface even in the event of a failed convertor pair
- Maintain GPHS surface within the 700°C to 1100°C range specified
- Consider radiation coupling the hot side to address CTE differences between the hot and cold structure
- Utilize proven microtherm and MinK insulation
- Consider venting generator during mission (convertors remain hermetic)
- Evaluate Back-to-back and head-to-head convertor arrangements
- Consider heat spreading on the cold side (heat pipes, k-core)
- Ability to transport within the 9904 shipping container

Head Interface

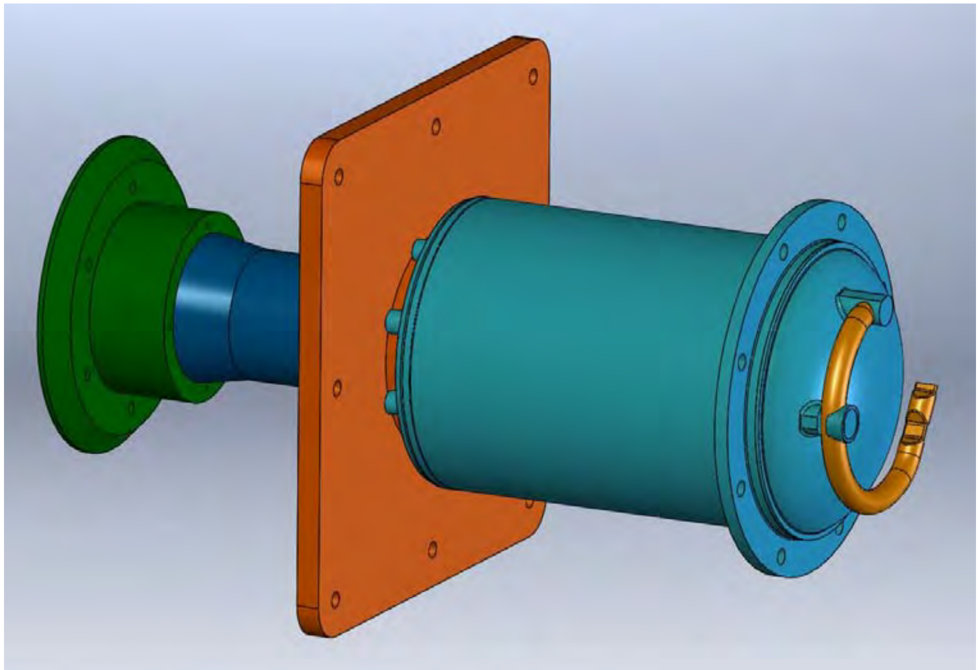
- SRSC will have a nickel block joined to the OD of the heater head
- Nickel block will either be clamped to a graphite heat distribution plate or use the nickel block itself for radiation heat transfer
- Side wall along heater head will also be tapered (not shown). Also will undercut flat face in area over head dome to reduced heat flow to dome.





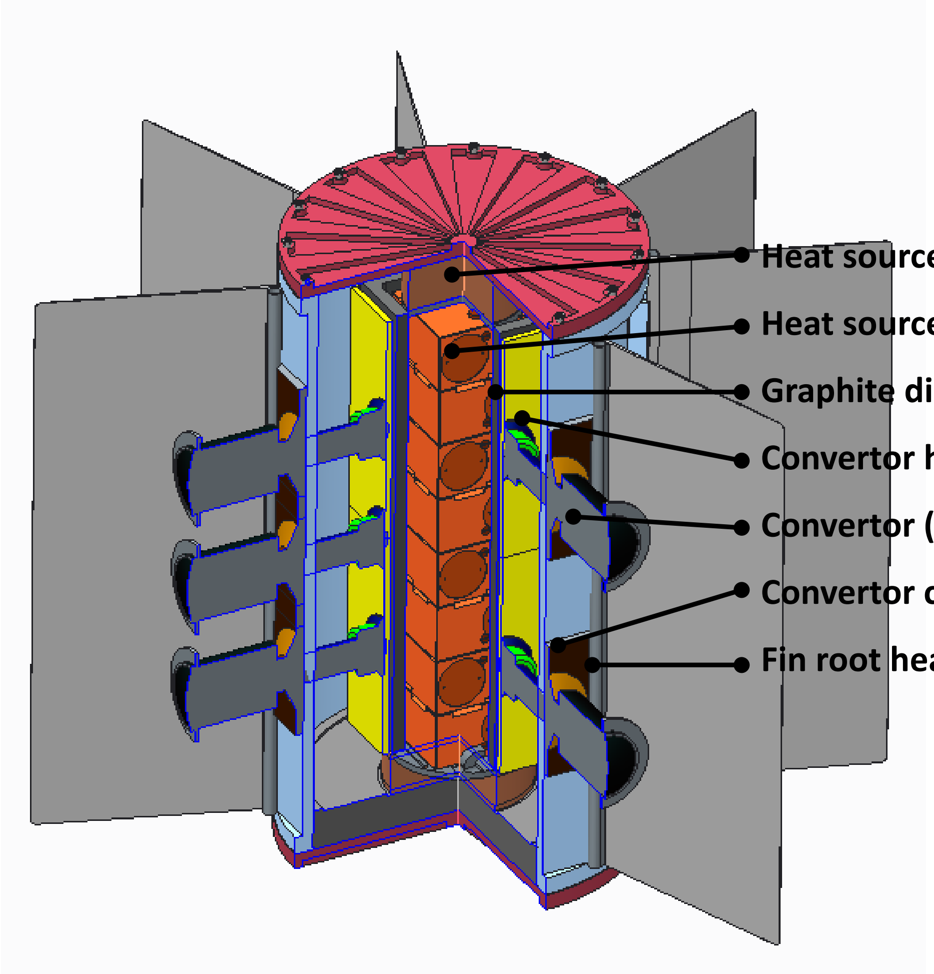
Reject Interface

- SRSC will continue to use a cold side adapter flange to provide the mounting structure and thermal contact area for the convertor
- CSAF is a square design to fit the generator layout
- Beryllium Copper construction, may need APG inserts to keep thickness down while maintaining a low enough delta T



Head to head – Redundant Convertor Pair

- Mimics RTG radial heat flow – radial heat flow
- Heat source with 8-GPHS modules
- Based on 64 W convertor size
- Includes a redundant convertor pair (8 required/10 installed)
- Cylindrical housing
- Heat source supported from the end caps
- Internal heat distribution to distribute heat in the event of a failed convertor pair (optional)
- Radiation coupled hot side to the convertor
- Nickel hot shoe for convertor input
- Copper cold side coupling similar to CSAF
- Heat spreading along the fin root
  - *K-core APG*
  - *Heat pipes could also be considered*



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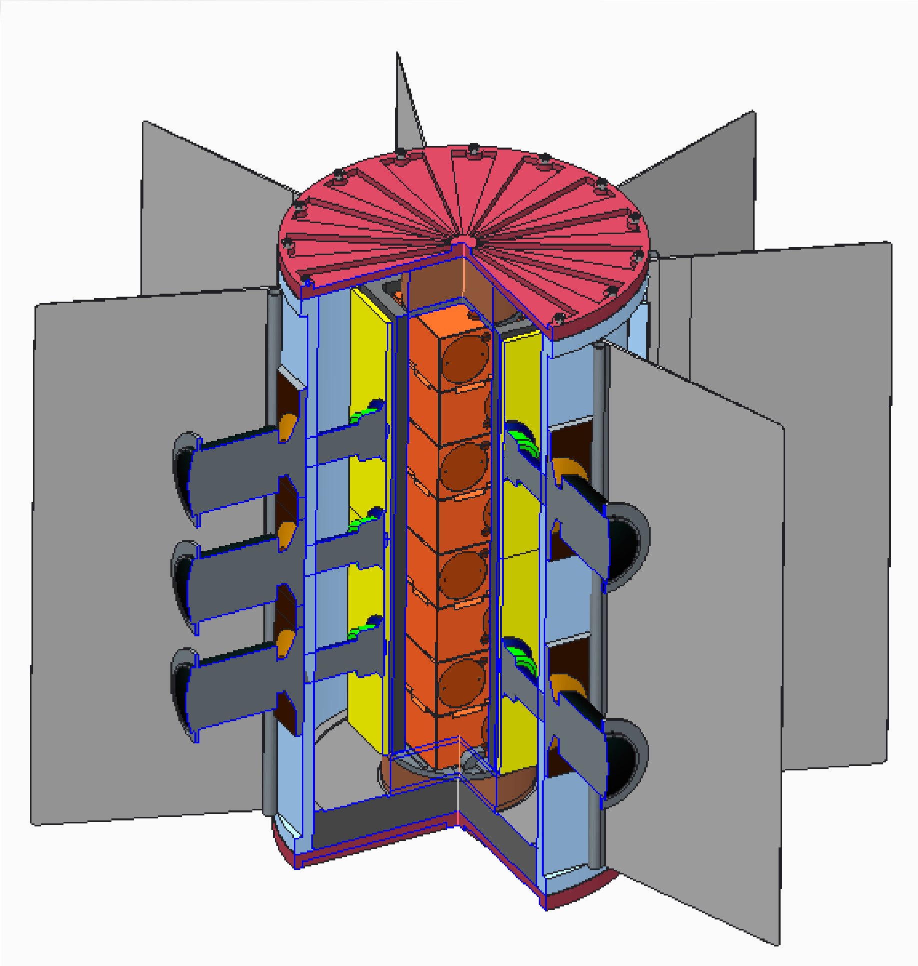
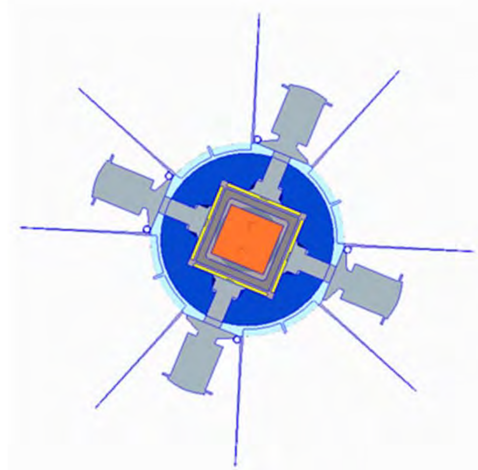
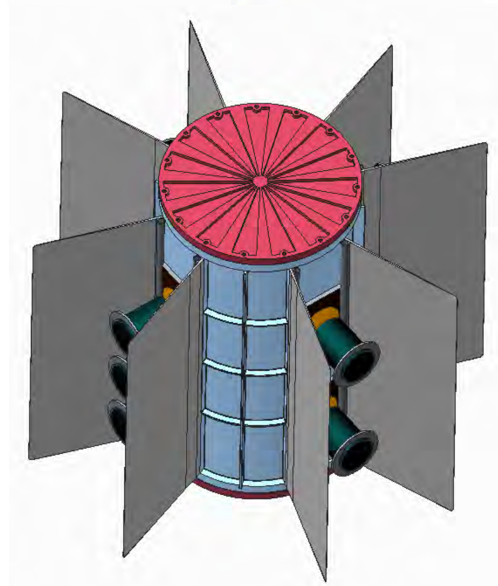
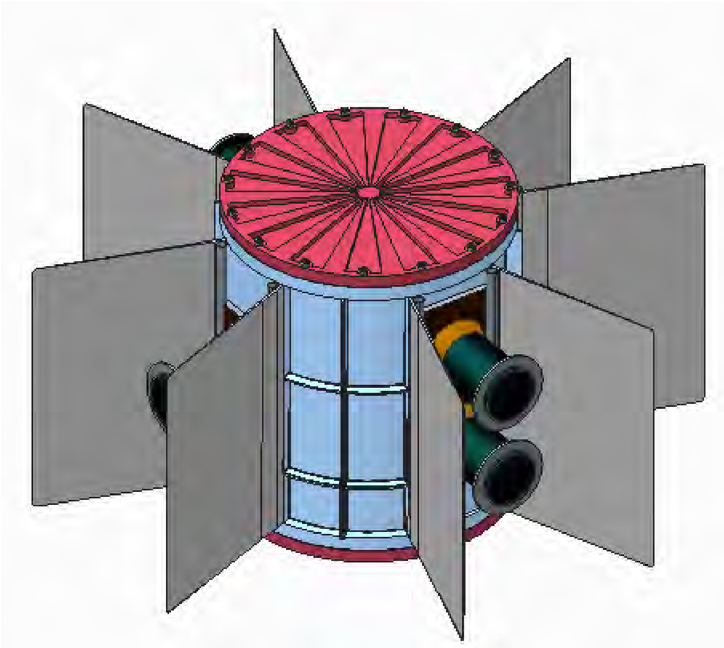
8-10 Radial (64 W Convertor Size)

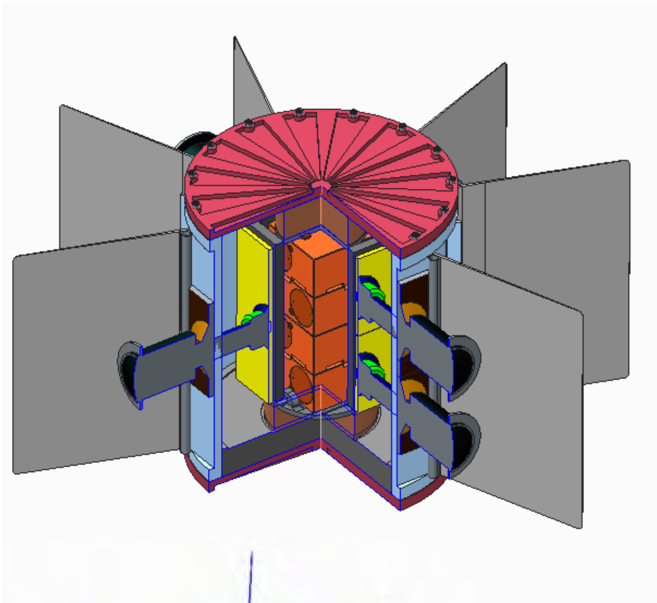


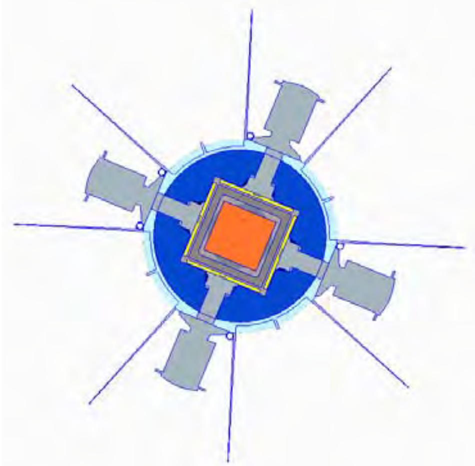




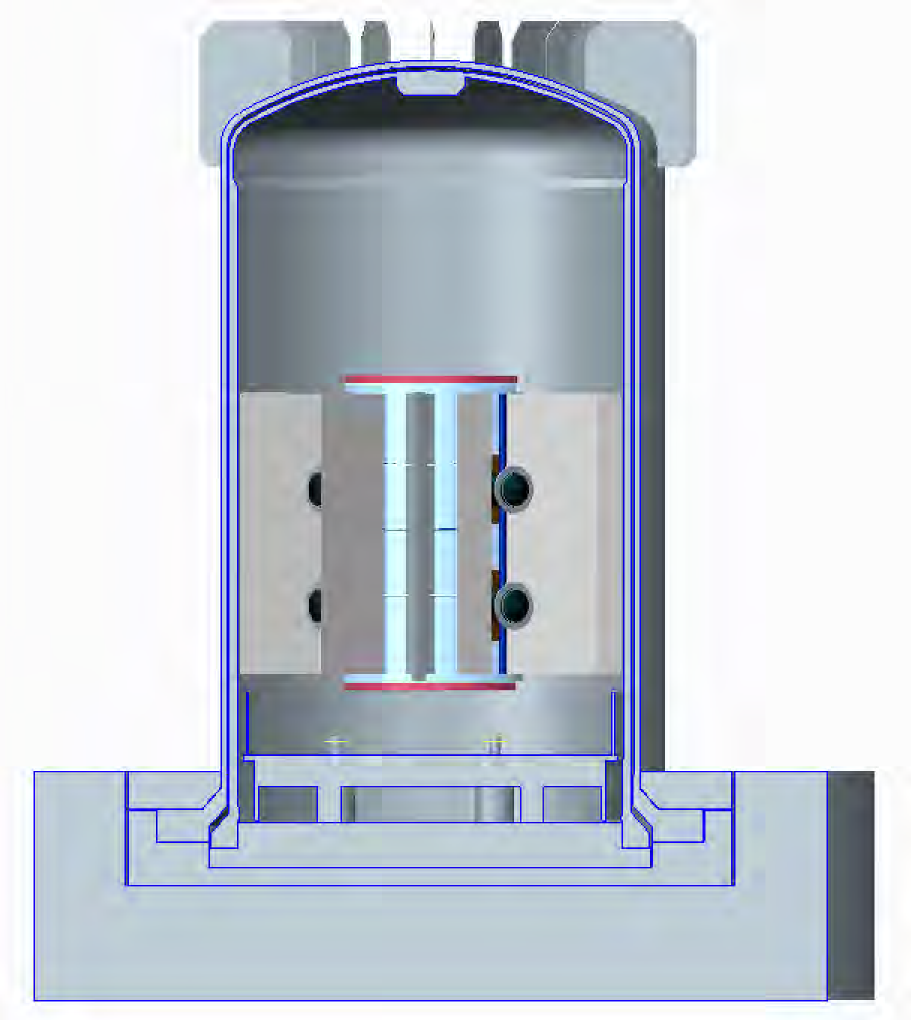
4 Block-6 Convertor Radial

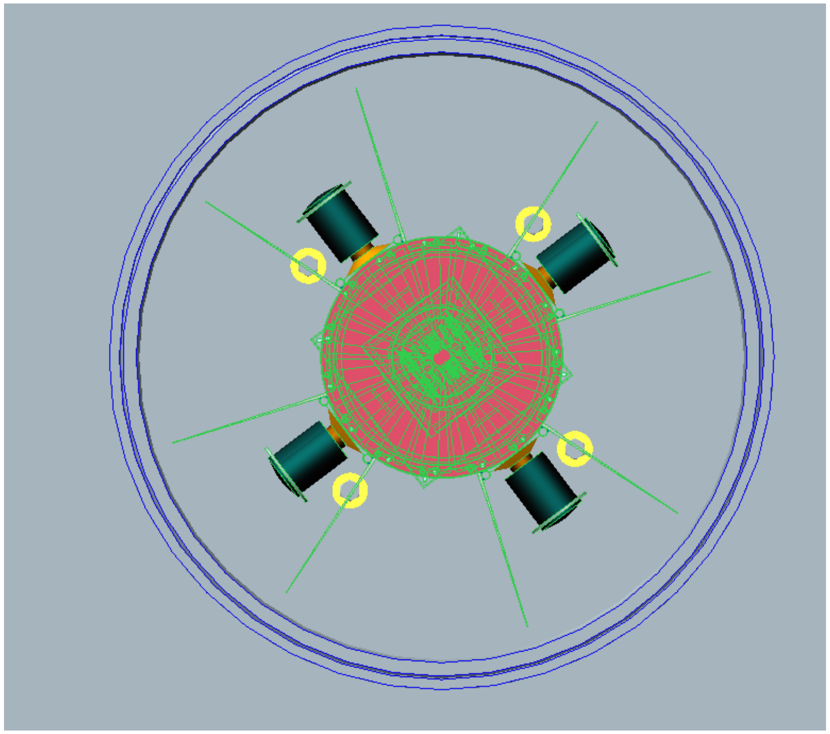






Radial System in Shipping Container





80 cm fin tip-to-tip

Summary

Sunpower Robust Stirling Convertor (SRSC)

- The SRSC design:
  - *Builds upon a mature Point of Departure design – ASC-E3*
  - *Incorporates design changes to address new requirements*
  - *Incorporates lessons learned and incorporates improvements identified in ASC-E3 Technology Readiness Assessment effort*
  - *Addresses community concerns (examples include start-up sequencing for testing and fueling)*
  - *Incorporates improvements/advancements from commercial cryocooler and engine efforts*
- Phase I scope is complete
  - *Trade Studies*
  - *Detailed design and performance predictions*
  - *Contract deliverables*
- Compliance with all requirements is expected
- Compliance with goals is expected
- Phase II expected to commence in June 2018

SRSC design features compared to POD

Design Feature	Design change	New Req't	Convertor Improvement		
			Robust	Reliable	Mfg
Regenerator	Cryocooler 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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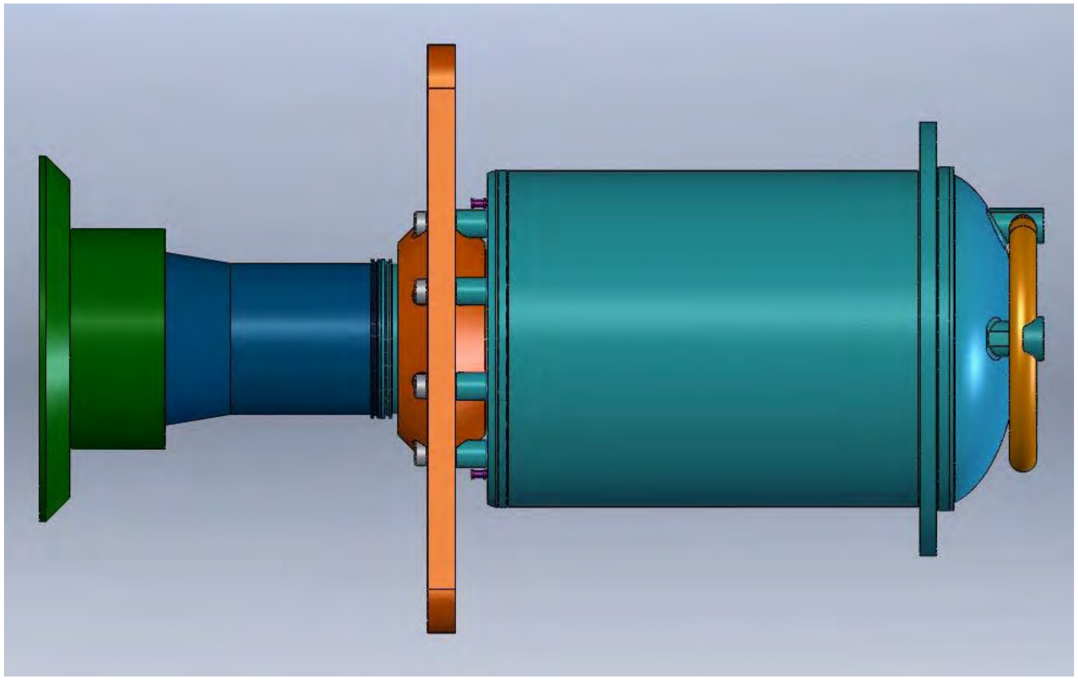
SRSC predicted compliance

Category	Requirement	Goal	Current Estimate
Design life	20 years of continuous operation at full power		Compliant
Convertor power output	Enables a 200 to 500 W_e generator		Compliant
Start-stop cycles	Capable of 150 start-stop cycles		Compliant
Launch vibration	No permanent loss of power or long-term effect from launch vibe		Compliant
Static acceleration	Capable of exposure to static and quasi-static accel with no permanent effect on performance:		Compliant
Performance degradation		Power decreases <0.5 % per year	Compliant
Thermal-to-electric conversion efficiency	≥ 24% with ≥100°C reject	≥28% with ≥100°C reject	29%
Partial power operation	Maintains ≥ 20% efficiency at 50% of design output power		27%
Hot-end operating temperature	< 1000 °C		CBE Th=720°C
Cold-end operating temperature	• Requires no less than 100 °C to meet efficiency		Compliant
	• Operation between 20 and 175 °C		Compliant
Thermal energy input	Designed to accept heat from an integer number of GPHS		Compliant
Atmospheric environment	Capable of operation in Earth, argon, vacuum, Mars Titan atm.		Compliant
Radiation		No loss of performance after exposure to 300 krad	Compliant
EMI		DC magnetic field	Compliant
Autonomy		• No operational adjustments needed during launch	Compliant
		• No adjustments needed during static acceleration	Compliant
Tolerance of loss of electrical load	Capable of loss of electrical load for 10 seconds while operating at full power, without any permanent effect on performance		Compliant
Transmitted forces	Enables a generator that reduces transmitted forces to the spacecraft to less than 10 N		Compliant
Specific power (W/kg)	> 20 W/kg (convertor only)		>30 W/kg
Size	Enables a generator design that will fit in the DOE shipping container:		Compliant
Manufacturability		Utilizes proven and effective MFG approaches	Compliant
Instrumentation necessary for flight convertor operation		Enables a long-life generator without the need for long-life sensors on the convertor(s)	Compliant
Performance measurement	Direct measurement of Th, Tr, Alternator, Xp, Xd. Not hermetic		Compliant

Thank you!



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