



CONVERTOR DEVELOPMENT FOR DYNAMIC RADIOISOTOPE POWER SYSTEMS

**2021 Conference on Nuclear and Emerging Technologies
for Space (NETS)**

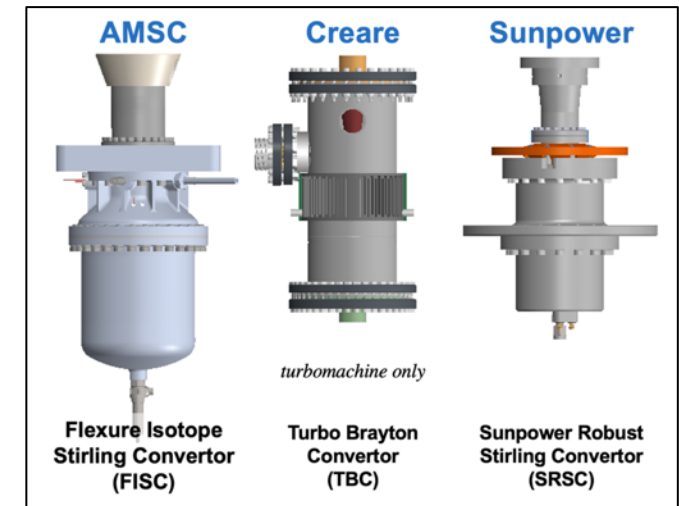
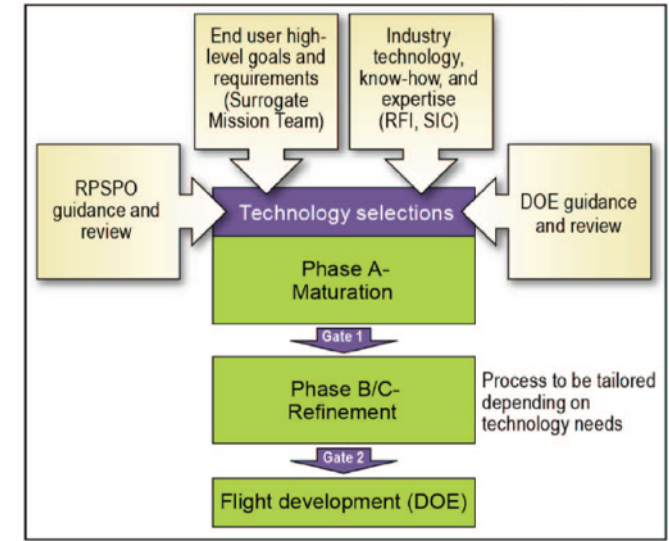
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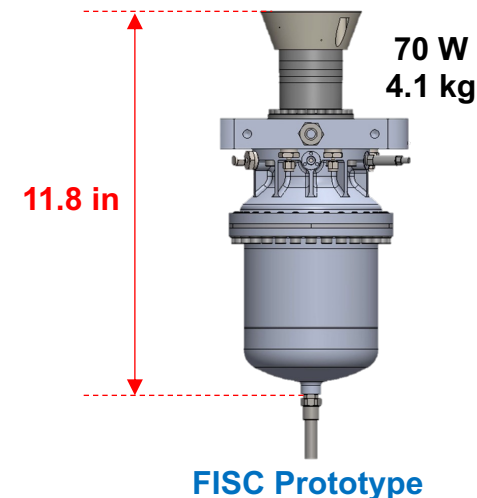
DRPS Technology Development Approach

- Dynamic Radioisotope Power Systems are being developed by NASA's RPS Program in collaboration with the DOE
- **Generator = Converter(s) + controller(s) + fuel + housing and support structure**
- Objective to mature one or more Dynamic Power Converter (DPC) technology to a sufficient level of readiness for flight development
 - Low degradation, high reliability, and high robustness
 - High specific power, high efficiency
 - Ease of use (minimize complexity during concept of operations)
- Technology development contracts based on multi-mission requirements
- Three contractors are delivering power converter prototypes
 - Flexure bearing free-piston Stirling
 - Hydrostatic bearing free-piston Stirling
 - Hydrodynamic bearing closed Brayton cycle
- Three phases: design, fabrication, and support during government V&V effort
 - Phase 1 started in 2017
 - Phase 2 started in 2018, longer than anticipated due to production and pandemic related delays
 - Phase 3 started in 2020 (one of three contractors have started so far)
- Prototypes will undergo Verification and Validation (V&V) campaign upon delivery to GRC



Flexure Isotope Stirling Convertor (FISC)

- **American Superconductor Corp. (AMSC) & Teledyne Energy Systems, Inc. (TESI)**
 - **Type:** Flexure-Bearing Free-Piston Stirling machine
 - **Basis:**
 - Technology Demonstration Convertor (TDC) SRG-110 Project – 16 prototypes and 2 engineering units were delivered between 2000-2006
 - Ongoing TDC prototype test holds world record for longest heat engine operation at 14.5 years and other units are still under test with over 14 years operation
 - TDC units have passed launch vibration and SES passed centrifuge testing
 - **Improvements:**
 - Higher bearing radial stiffness
 - Higher cold-end temperature capability
 - More hot-end temperature margin
 - Higher efficiency alternator
 - Improved alignment surfaces
 - Independently verifiable subassemblies
 - Overstroke tolerance (bumpers)



TDC #13 on extended operation at GRC



FISC #1 prototype at AMSC

Flexure Isotope Stirling Convertor (FISC)

- **Status**

- Phase 2 – Production is ongoing

- **Contractor Results**

- ✓ Implemented corrosion resistant regenerator (random fiber)
 - ✓ Demonstrated new high efficiency alternator
 - ✓ Demonstrated full and partial power conversion efficiency (retest underway to confirm results)

- ✗ Partial power efficiency not met on FISC #2, 0.4 % below requirement

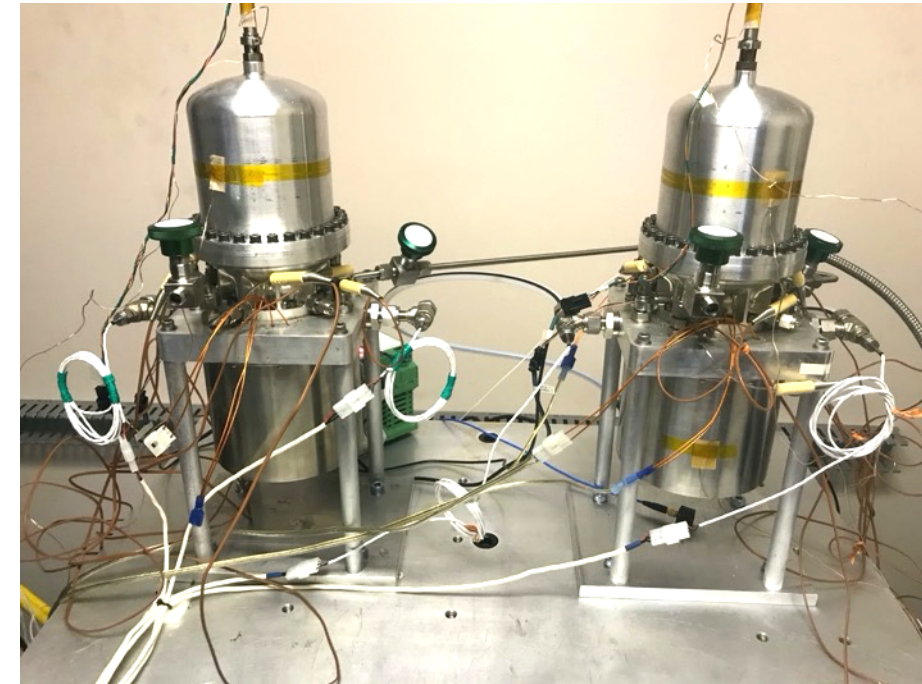
- ✗ Maximum reject temperature of 175 °C not met due to insufficient temperature limit for some non-flight features in alternator

- ✗ Specific power was not met, 4 We/kg below requirement

- ✓ All other requirements met via test or analysis

- Prototypes #1 and #2 are planned for delivery in Summer 2021

- Units will enter government Verification and Validation (V&V) test effort upon delivery

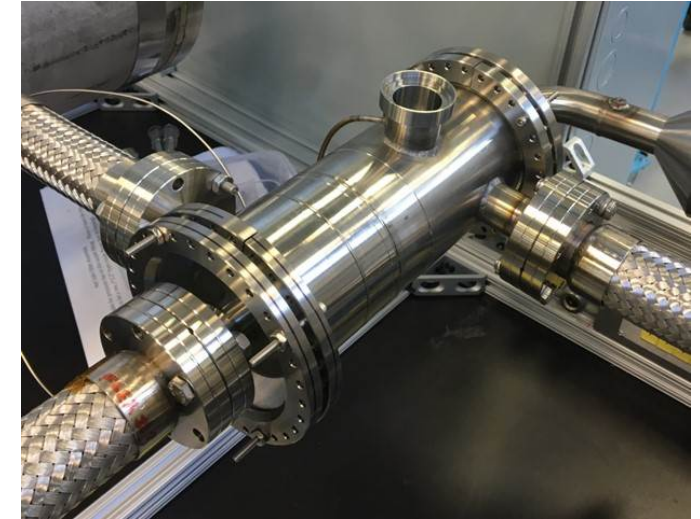


FISC Prototypes #1 and #2 on test at AMSC

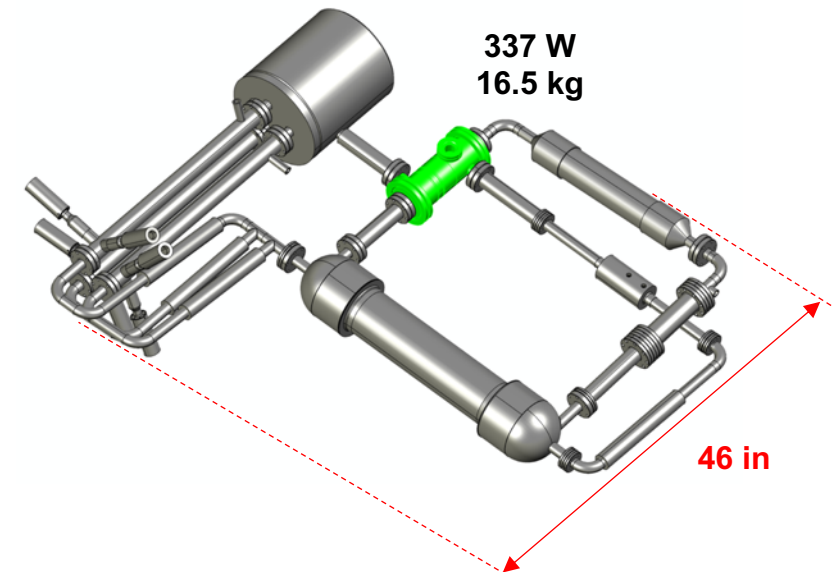
Turbo Brayton Convertor (TBC)

- **Create, LLC & Aerojet Rocketdyne**

- **Type:** Hydrodynamic Gas-Bearing Closed Brayton Cycle machine
- **Basis:**
 - Previous NASA NRA and SBIR designs
 - NICMOS Cryocooler operated 6.5 yrs on orbit aboard the Hubble Space Telescope
- **Improvements:**
 - Dedicated thrust bearing
 - Higher cold-end temperature capability
 - Recuperator uses advanced fabrication methods
 - Two units permits system redundancy
 - Contains diagnostic radial position sensors



Prototype Turbomachine at Create



TBC Prototype Layout
turbo machine highlighted

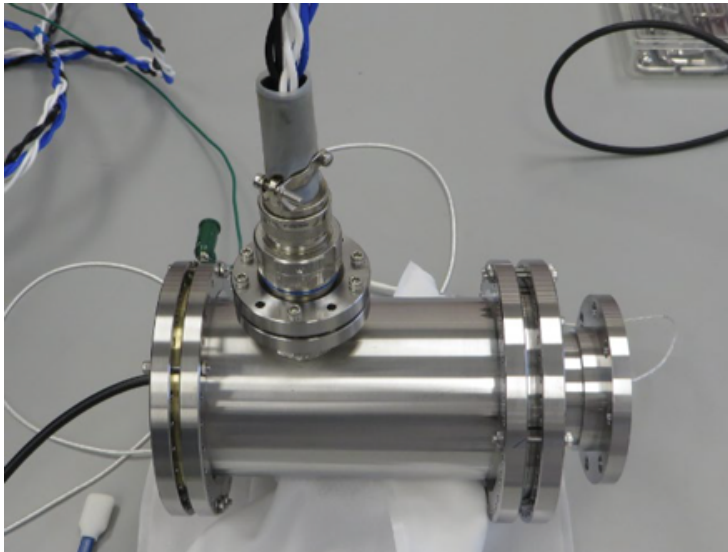
Turbo Brayton Converter (TBC)

- **Status**

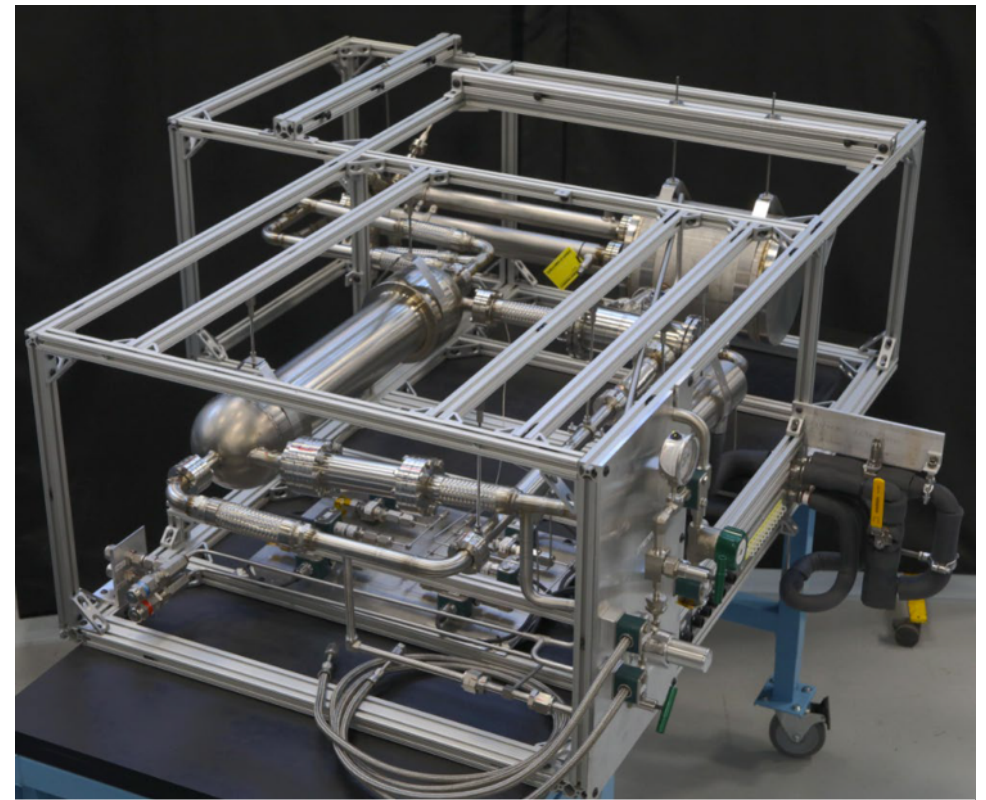
- Phase 2 – Production is ongoing

- **Contractor Results**

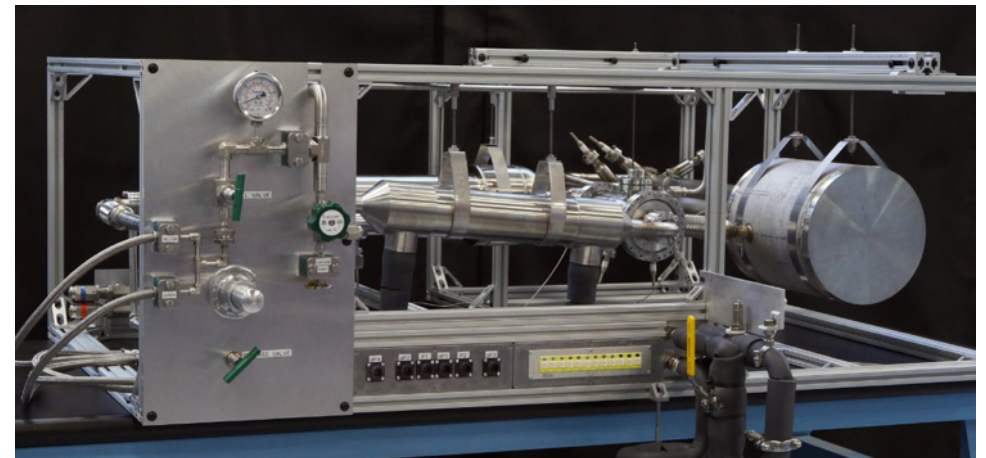
- One prototype is being prepared for delivery in Summer 2021, test results are pending
 - One dedicated Brayton Vibration Test Article is being prepared for random vibration testing
 - Duplicates the prototype bearings to test them under representative conditions and verify no contact during launch environment



Dedicated Brayton Turbomachine Test Article



TBC #1 Prototype at Creare (view 1)

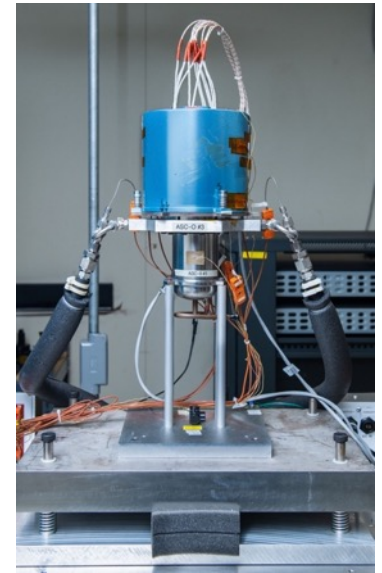
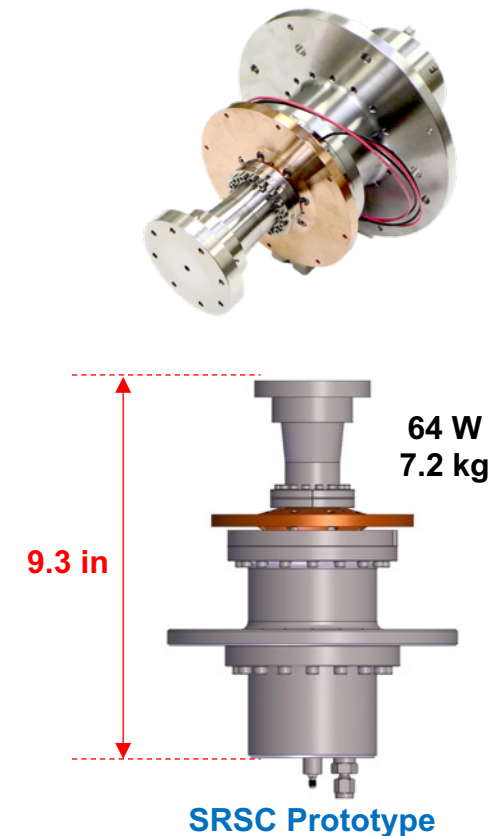


TBC #1 Prototype at Creare (view 2)

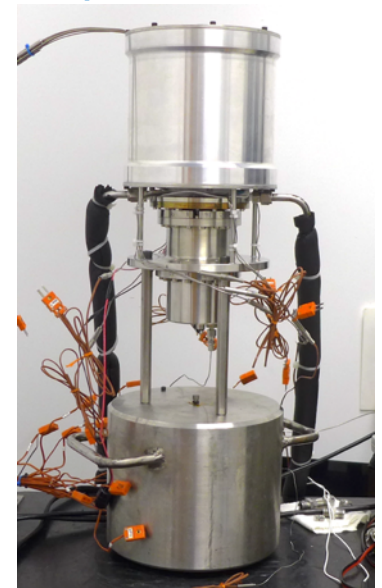
Sunpower Robust Stirling Convertor (SRSC)

- **Sunpower, Inc. & Aerojet Rocketdyne**

- **Type:** Hydrostatic Gas-Bearing Free-Piston Stirling machine
- **Basis:**
 - Advanced Stirling Convertor (ASC) from ASRG Project – 17 prototypes and 20 engineering units were delivered between 2007-2015
 - Ongoing ASC prototype has exceeded 11 years of operation
 - ASC units have passed launch vibration and centrifuge testing
- **Improvements:**
 - Higher bearing load capacity
 - Higher cold-end temperature capability
 - Centering spring on piston to ease startup
 - Robust regenerator to eliminate potential for debris
 - Alternator robustness improvements
 - Overstroke tolerance (passive collision prevention system)



ASC-0 #3 extended operation at GRC



SRSC #1 prototype at Sunpower

Sunpower Robust Stirling Converter (SRSC)

- **Status**

- Phase 2 Production was completed for the two units in June and September of 2020
- Prototypes #1 & #2 were delivered to NASA in October 2020

- **Contractor Results**

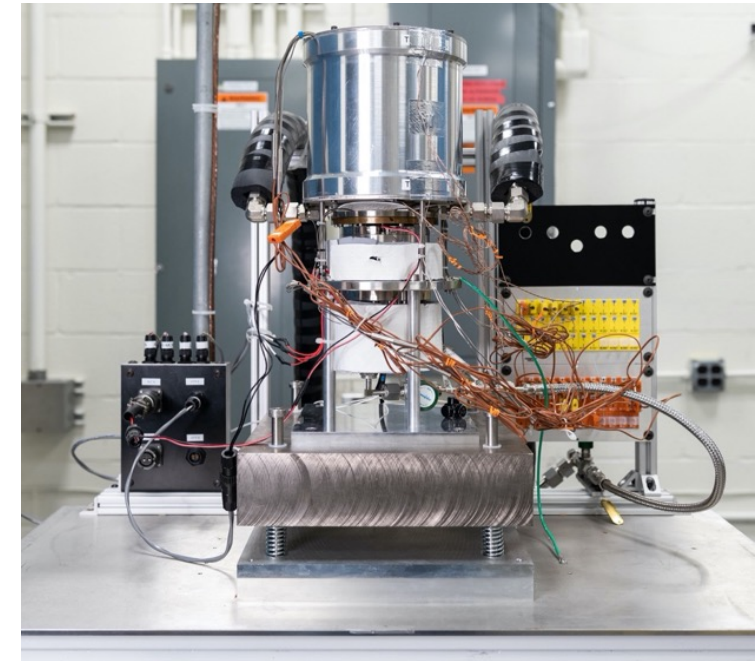
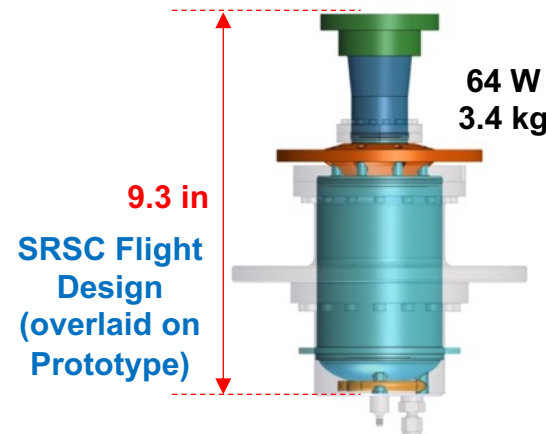
- ✓ Robust regenerator design implemented (wrapped screen)
- ✓ Demonstrated maximum reject temperature of 175 °C
- ✓ Demonstrated 10-sec loss of electrical load using passive collision prevention system during (dissipates energy at very high piston amplitudes)
- ✓ Robust position sensors (potential for flight)
- ✗ Efficiency for full power and partial power was not met, 2-3% below requirement (primarily due to new regenerator design)
- ✓ All other requirements met via test or analysis

- **Phase III Started**

- Support for government testing
- Two additional units are under production
 - Conforming efficiency
 - Hermetically sealed flight design



SRSC #1 & #2 delivered to GRC in Oct 2020



SRSC #1 under test at GRC

V&V Plan – Purpose, Scope, and Applicability

Objective to verify requirements using test and analysis

- **Track 1 (Performance)**

- Acceptance
- Verify performance
- Baseline data

- **Track 2 (Vibration Testing)**

- Random vibration
- Optional inspection

- **Track 3 (Centrifuge Testing)**

- Constant acceleration
- Optional inspection

- **Track 4 (Robustness Testing)**

- Thermal cycling
- 10-sec loss of load

- Material testing also planned to verify creep life, radiation tolerance, and compatibility of organic materials
- Tracks 1-4 plan takes 1 year to execute, steady operation confirms no damage after environmental testing
- Longer durations are being experienced during pandemic, compared to the original planning

Category	Description
Convertor power output	Enables a 200 to 500 W _e generator
Start-stop cycles	Capable of 150 start-stop cycles
Launch vibration	Acceleration Spectrum Denisty
Static acceleration	Full pwr: 5 g for 5 days in all axes
	Full pwr: 20 g for 1 minute in all axes
Performance Degradation	Output power decreases <0.5 % per yr
Thermal-to-electric conversion efficiency	≥ 24% for Trej ≥100 C
Partial power operation	Maintains ≥ 20% efficiency when input heat is 50% of design
Hot-end operating temperature	< 1000 °C
Cold-end operating temperature	Capable of Trej from 20 and 175 °C
Thermal energy input	Designed for GPHS-Step 2 modules
Radiation	No loss of performance after exposure to 300 krad
Tolerance of loss of electrical load	Survive loss of electrical load for 10 seconds at full power
Transmitted forces	Enables generator with <10 N of transmitted forces to s/c
Specific Power	>20 We/kg (convertor only)
Size	Generator design fits in DOE shipping container

Track 1 – Performance Verification

- Sunpower SRSC #1 and #2 V&V Progress:
 - ✓ Receipt and Inspection: Completed
 - ✓ Acceptance testing: Completed
 - ✓ Insulation Loss Test: Completed
 - Performance Mapping in progress
- SRSC Temperatures
 - ✓ Hot end temperature 700 °C: Completed
 - ✓ Nominal rejection temperature 100 °C : Completed
 - ✓ Maximum rejection temperature 175 °C: Completed
 - Minimum rejection temperature 20 °C in progress
- Purpose of performance mapping is to verifying convertor performance in the delivered support structure
- Next steps include installing convertors into GRC support structure (appropriate for extended duration testing) and collection of baseline data to serve as comparison after each environmental test is completed



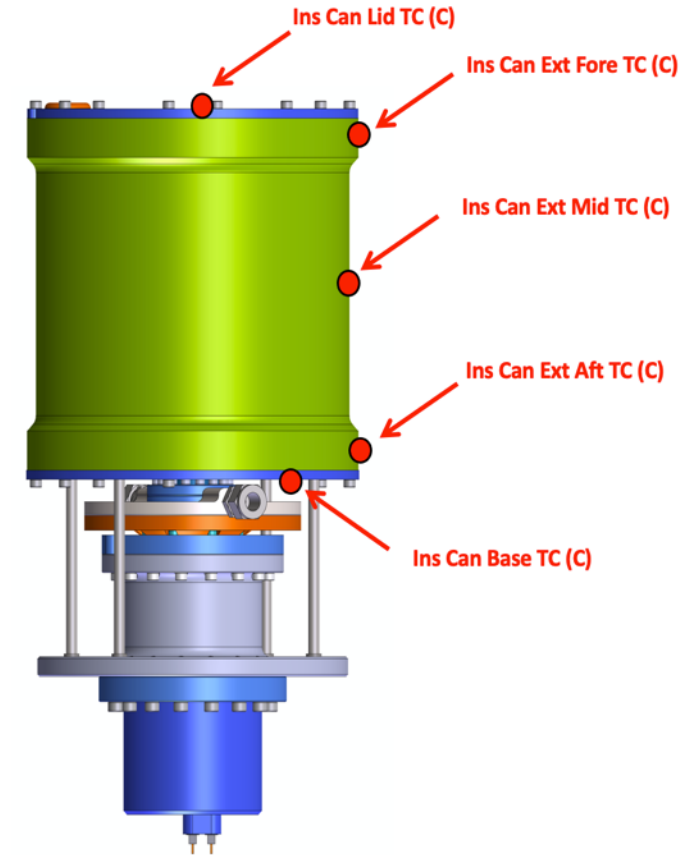
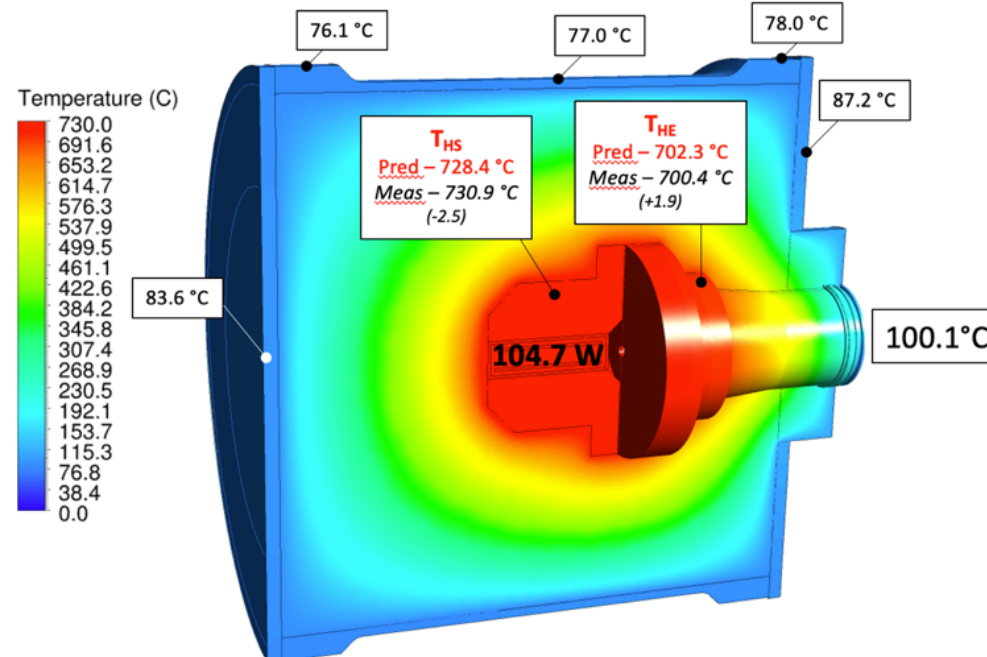
SRSC #1 & #2 testing in Stirling Research Lab at GRC



SRSC #1 testing in Stirling Research Lab at GRC

SRSC Thermal Analysis Performed During Track 1

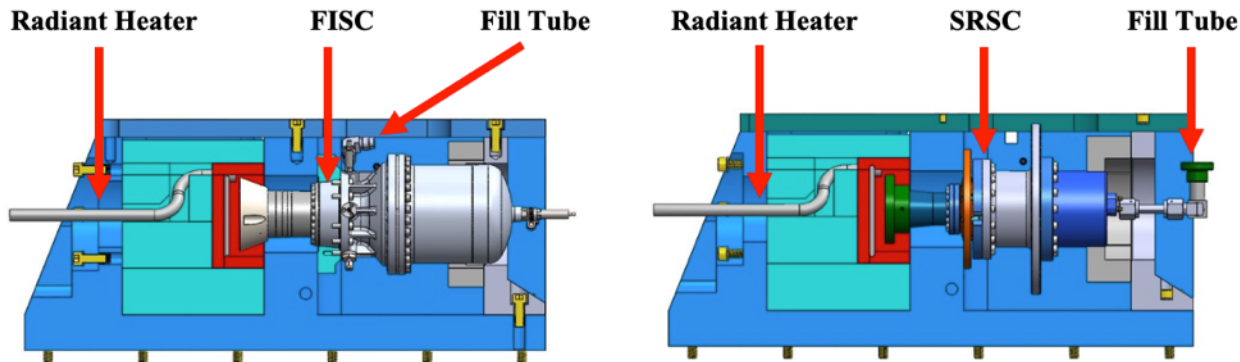
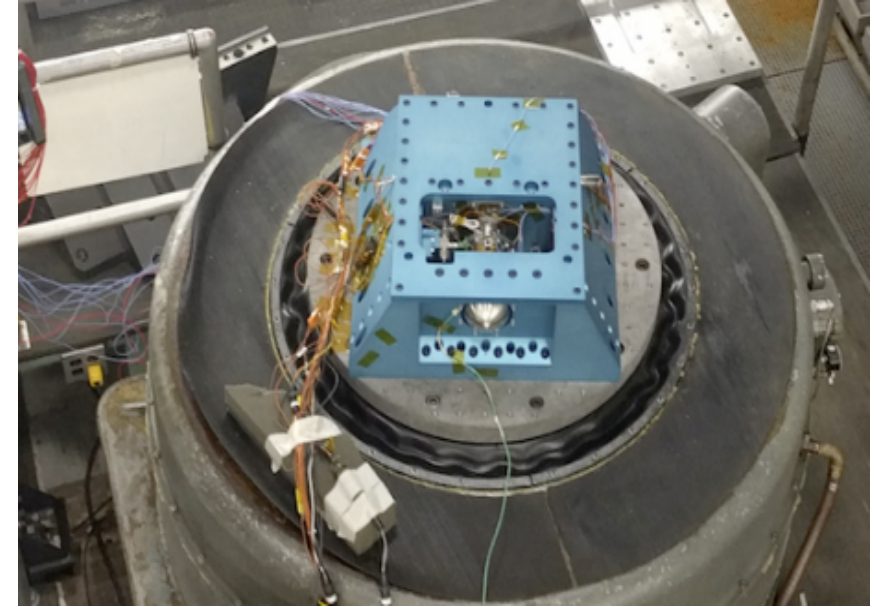
- Calculations of prototype thermal conversion efficiency will be made possible using 3D CFD analysis results – in progress now
 - Based on method developed and verified during ASRG
 - Test measurements are used as boundary conditions to limit heat transfer in complex geometry
- ✓ **Step 1 – Calibrated model using thermal loss test results: Completed**
- **Step 2** - Predict net heat input to Stirling expansion space by performing multiple cases and interpolating heat input value that ensures numerous internal temperatures match test results



Track 2 – Vibration Testing

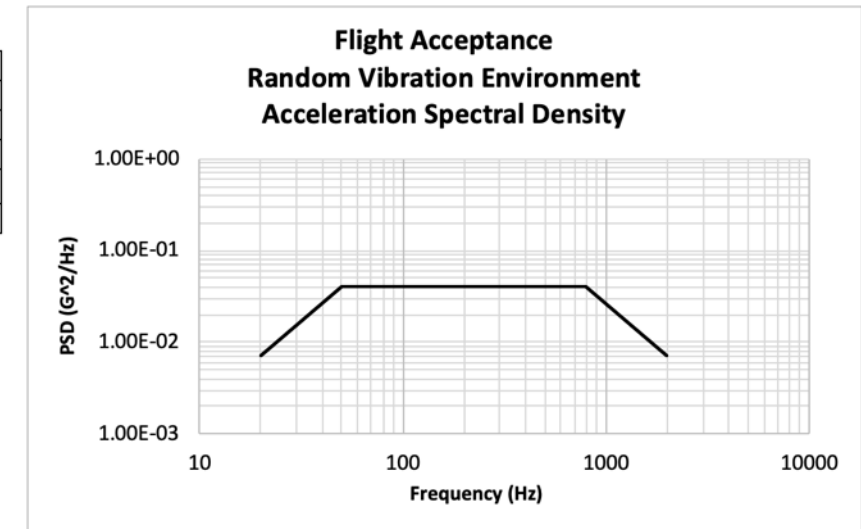
- Simulates external forces due to launch environment
- Prototypes designed to 10.35 Grms
- TBC prototype will not be vibe tested - a dedicated Brayton Turbomachine Test Article will be vibe tested instead
- Radiant heater planned to simulate radiant coupling to GPHS utilized in contractor generator concepts
- Stirling convertors are mounted at rejection flanges and at the alternator to best simulating generator level mounting configurations
 - Heater heads are cantilevered in this configuration

Vibe Testing at GRC's Structural Dynamics Laboratory



Ref. Generator Req. from SOW

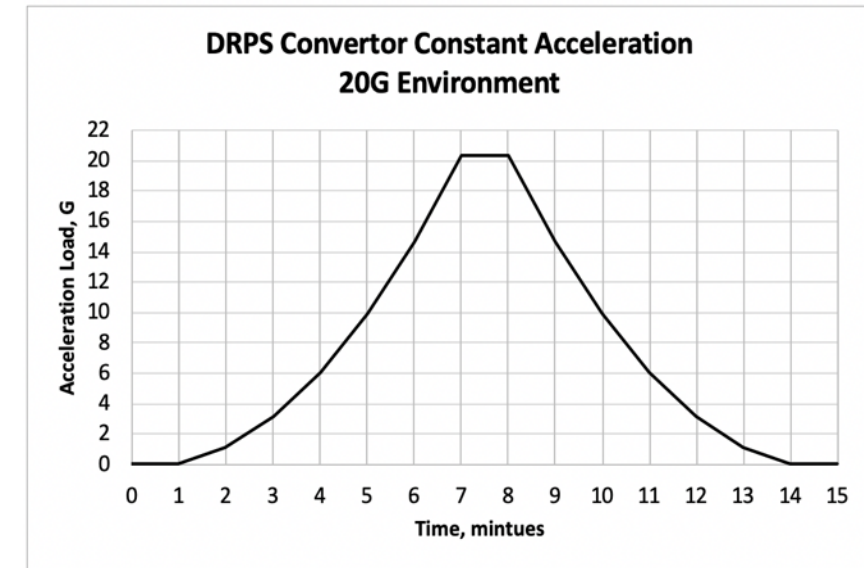
Freq (Hz)	PSD (G ² /Hz)
20	7.00E-03
50	4.00E-02
800	4.00E-02
2000	7.00E-03
Overall	7.1 Grms



Track 3 – Constant Acceleration

- Simulates external force due to spin stabilization just after launch (5 g) and aerobraking during EDL (20 g)
- Test objective to demonstrate no wear under 5g lateral load for 5 days requirement
 - May not be able to test for 5 days and desire multiple orientations to capture any production variability
 - Plan to test four orientations in lateral direction for 6 hours each
 - Desired 5-day test being investigated
- Verify ability to survive without permanent degradation after 1-minute exposure to 20g acceleration requirement
 - Plan to test two lateral directions and two axial directions
- TBC Prototype won't fit in centrifuge so plan to test the dedicated Brayton Turbomachine Test Article

Centrifuge Test Facility at Case Western Reserve University (CWRU)



Track 4 – Robustness Testing

Thermal cycling

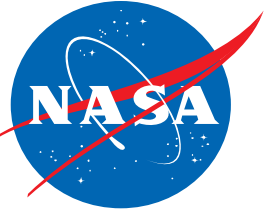
- Verifies geometric stability of close clearance bearing surfaces
 - Plan ensure all prototypes have completed a total of 30 cycles, including production testing

10-sec loss of load

- Verifies robustness to loss of electrical load during ground errors or during piston amplitude excursions caused by launch environment
 - Plan to forgo this test on SRSC Pair 1 due to overtest conditions (it was previously verified during Phase 2: SRSC #1 underwent 40 seconds of unloaded testing while SRSC #2 underwent 60 seconds)
 - Plan to forgo this test on FISC Pair 1 (insufficient margin for bumpers)
 - Plan to pursue this test on TBC (to be finalized at end of Phase 2)

Summary

- Three technologies are being developed and the results are not yet final
- Sunpower SRSC prototypes were delivered and started V&V testing at GRC, initial efficiency was low, hermetic units are under production to increase TRL and meet efficiency requirement
 - Paper #36541, “Sunpower Robust Stirling Convertor (SRSC) Phase II Overview”
- AMSC FISC prototypes will be delivered in near term, initial results show they meet most efficiency requirements, specific power and rejection temperature requirements were not met, improvements are being considered
- Creare TBC prototype initial testing is planned in near term, as well as random vibration test of dedicated Brayton Vibration Test Article, delivery is anticipated later this Summer
 - Paper #35967, “Turbo Brayton Converter for Radioisotope Power Systems”
- V&V Plan intends to demonstrate TRL 6 at subsystem level
- Results are provided to future technology readiness assessments and DRPS gate reviews that support flight development



Special thanks to:

- RPS Program Office and DRPS Project
- Stirling Research Lab Team
- AMSC Team, Creare Team, Sunpower Team

Thanks for your attention!