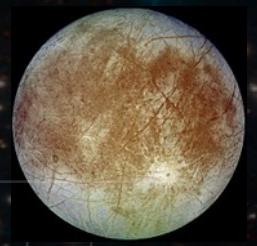
National Aeronautics and Space Administration



MATURATION OF DYNAMIC POWER CONVERTORS FOR RADIOISOTOPE POWER SYSTEMS

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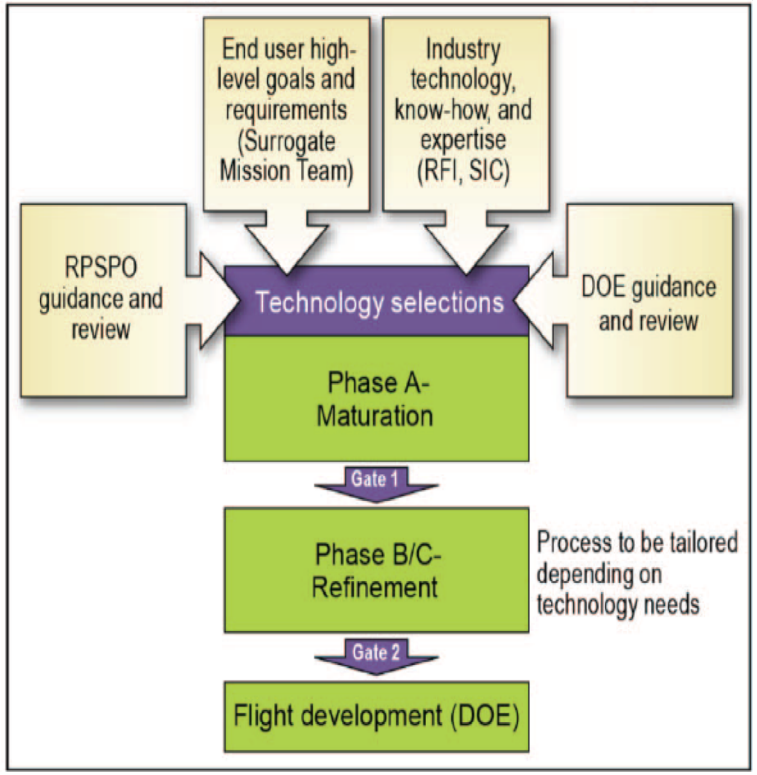
Maturation of Dynamic Power Convertors

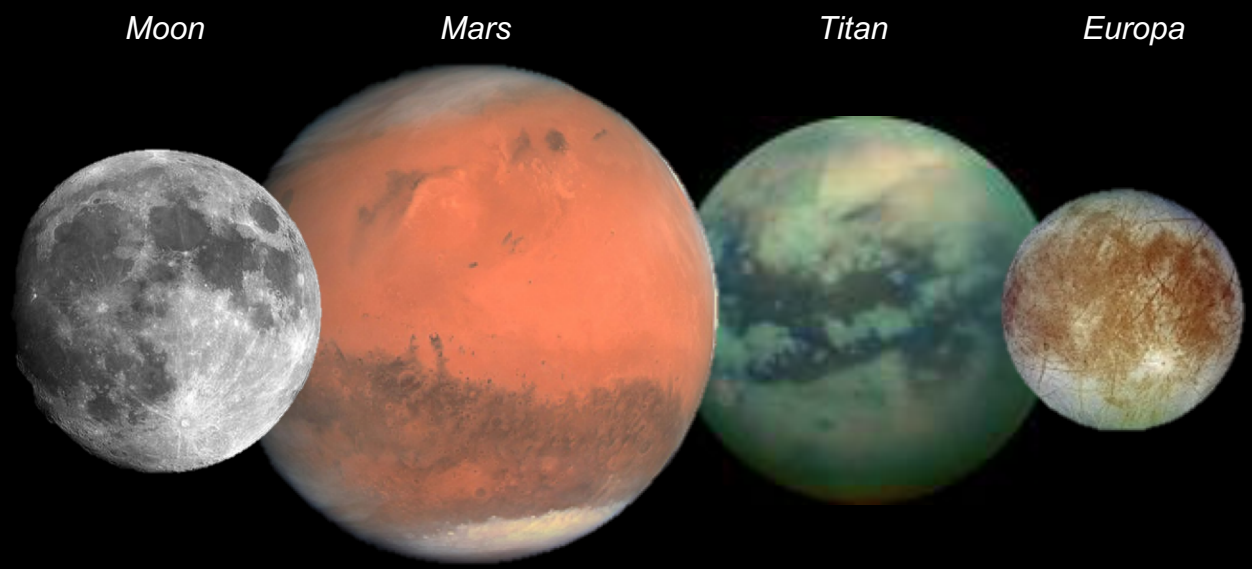
- **Radioisotope Power Systems Program** implemented maturation model developed for other projects
  1. Established a Surrogate Mission Team (SMT) to provide clear mission pull and requirements context
  2. Execute the evaluation model to mature available technologies to a TRL that is suitable for flight development
- **Surrogate Mission Team** (SMT) developed the multi-mission requirements used in the technology maturation contracts
- **Risk Informed Life Testing** (RILT) model
  - Was designed to quantify the likelihood that components and subassemblies will meet life goal with margin
  - Is being used to identify components and materials that need improved life data
- **Integrated Product Team** (IPT) formed by the project
  - To monitor contract progress to identify risk of insufficient margin
  - Identify potential testing or analysis to address risks



Requirements & Environments

Item	Description
Design Life	20 years continuous operation at full power
Power	Suitable for a 200 to 500 W_e generator
Efficiency	≥ 24% at $T_{cold\text{-}end}$ ≥ 100 °C
Specific Power	20 We/kg (convertor only)
Degradation	Output power changes < 0.5 % per year
Partial power	Maintains 20% conversion efficiency at 50% heat input
Atmosphere compatibility	Earth, Mars, Titan, vacuum, Argon
Hot-End Temp	< 1000 °C
Cold-End Temp	Capable of 20 to 175 °C
Random Vibe	Launch spectrum for 1 min in each axis
Static Accel	20 g for 1 minute, 5 g for 5 days
Tolerance to Loss of Load	Survive a loss of electrical load for 10 seconds while at full power
EMI	< 100 nT at 1 m while at full power
Radiation	No degradation after exposure to 300 krad
Autonomy	No external commands needed
Transmitted Forces	Enables generator with less than 10 N transmitted forces to spacecraft
Size	Enables generator for shipping cask

- Surrogate Mission Team (SMT) membership from major robotic mission centers and agency partners (RPS Program, DOE, GRC, JHU-APL, GSFC, JPL)
- SMT used target environments as basis for requirements development



DPC Contracts

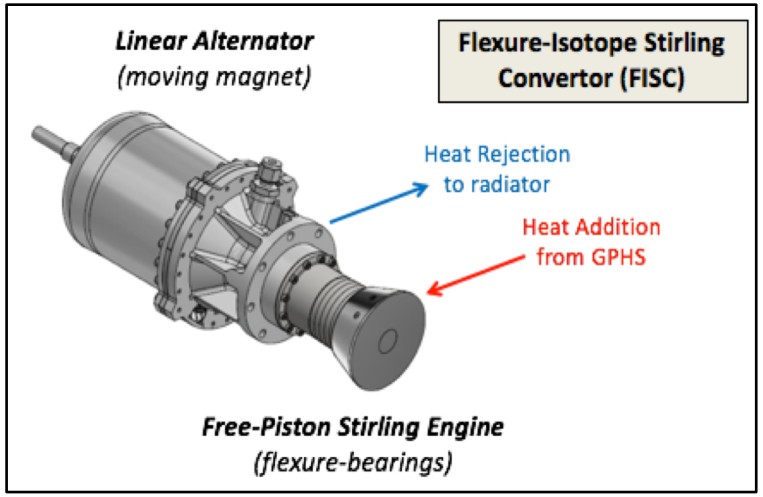
- **Formulation**

Phase	Duration	Contractor Work	Government Work
1	6 months	Design	Review Risk Informed Life Testing analysis
Decision Gate 1 (move to gate 2?)			
2	18 months	Fabrication & Test	Review IV&V Plan, test facility preparation
Decision Gate 2 (recommend for flight development?)			
3	12 months	Support	IV&V testing and analysis Model validation
Potential Decision Gate n			

Dynamic Power Convertors for RPS Contracts

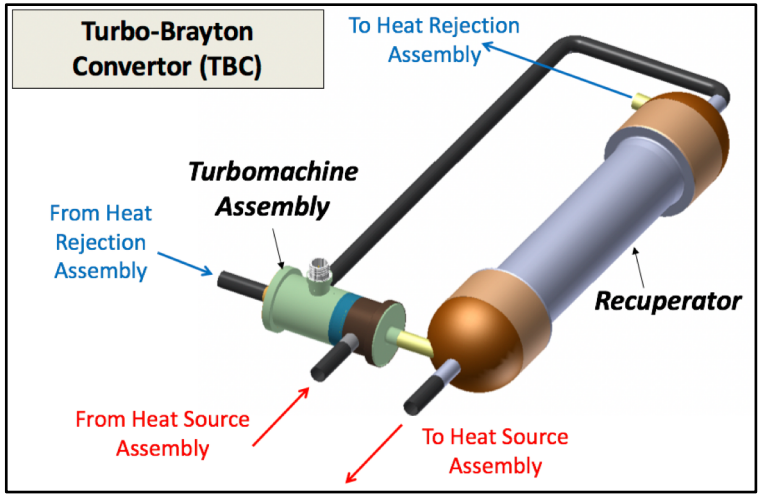
Flexure-Isotope Stirling Convertor (FISC)

- **American Superconductor Corp (AMSC)**
- **Flexure bearing**
- **TDC derivative**
- **Engineering challenges:**
  - Close clearance non-contacting seals, high-cycle fatigue, high-temp creep, high-temperature rejection
- **Status:** Production in progress, 50% through Phase 2



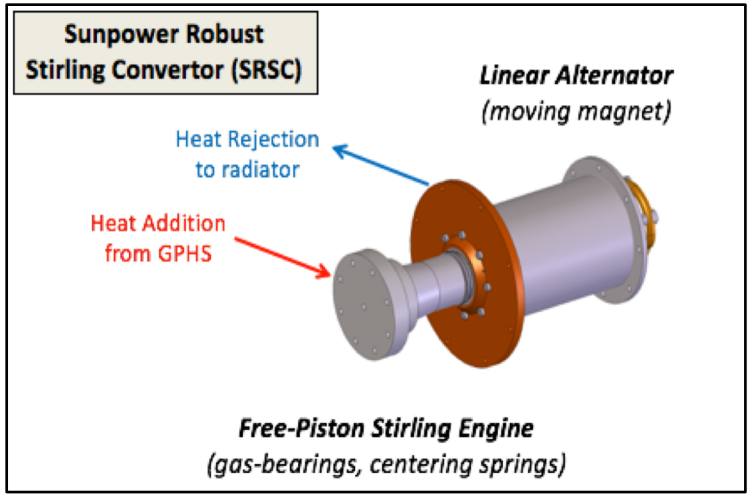
Turbo-Brayton Convertor (TBC)

- **Creare**
- **Hydrodynamic gas bearing**
- **Cryocooler derivative**
- **Engineering challenges:**
  - Close clearance non-contacting seals, high-performance heat exchangers, high-temp creep, high-temperature rejection
- **Status:** Production in progress, 50% through Phase 2

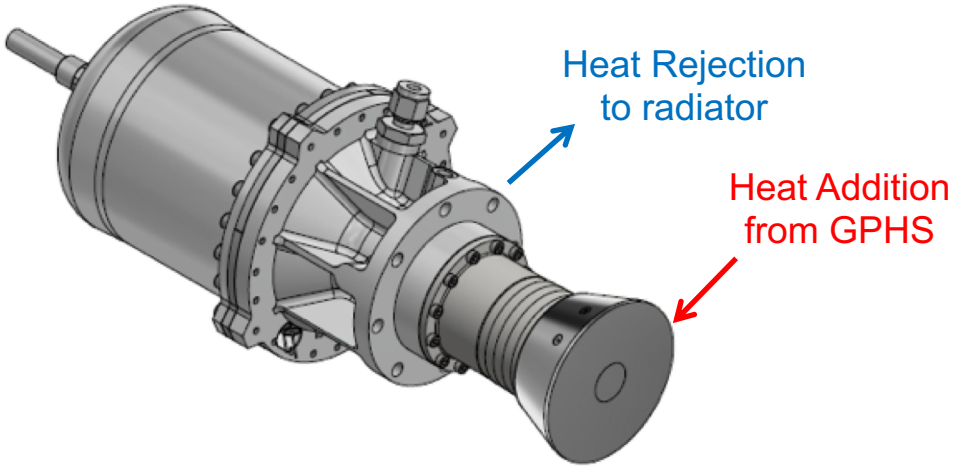


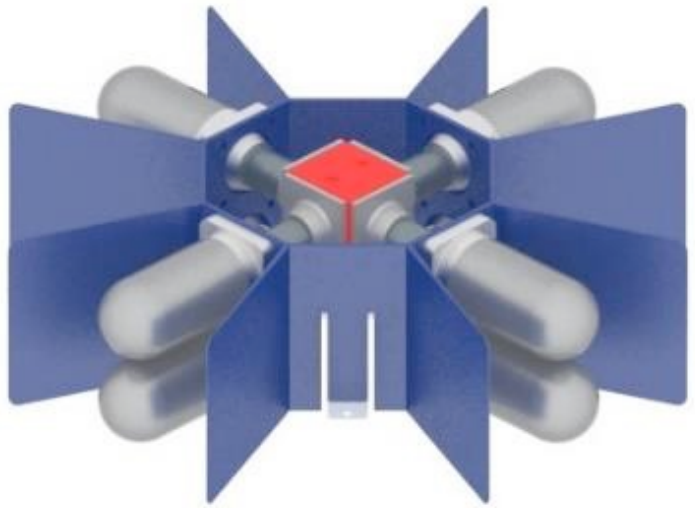
Sunpower Robust Stirling Convertor (SRSC)

- **Hydrostatic gas bearing (Sunpower Inc.)**
- **ASC derivative**
- **Engineering challenges:**
  - Close clearance non-contacting seals, high-cycle fatigue, high-temp creep, high-temperature rejection
- **Status:** Production in progress, 40% through Phase 2



Flexure Isotope Stirling Convertor (FISC)





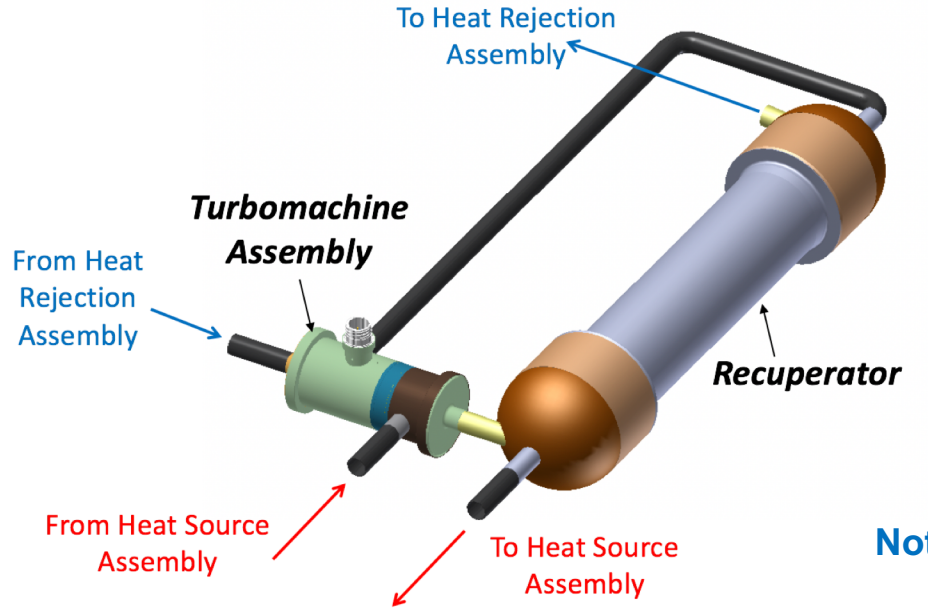
Notional 250 W generator concept with 100% convertor redundancy (4 required, 8 installed, 4 GPHS's)

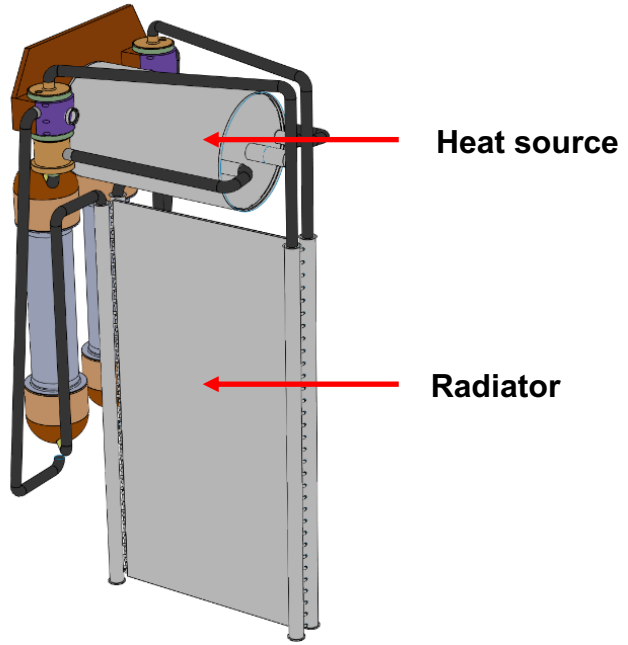
Design Parameters

Hot-end Temp	650 °C
Cold-end Temp	20 to 175 °C
Efficiency	31% @ T_{COLD}=100°C
Power Output	70 W_{ac}
Mass	3.3 kg (>20W_e/kg)

- Flexure-bearing based free-piston Stirling convertor
- Derivative of Technology Demonstration Convertor (TDC) from a 1990's SBIR and SRG-110 project
- **Design deltas relative to TDC to improve the following:**
  - Higher radial stiffness flexures, overstroke tolerance, hot-end temperature margin
  - Independently verifiable subassemblies
  - Higher efficiency alternator, higher cold-end temp capability

Turbo-Brayton Convertor (TBC)





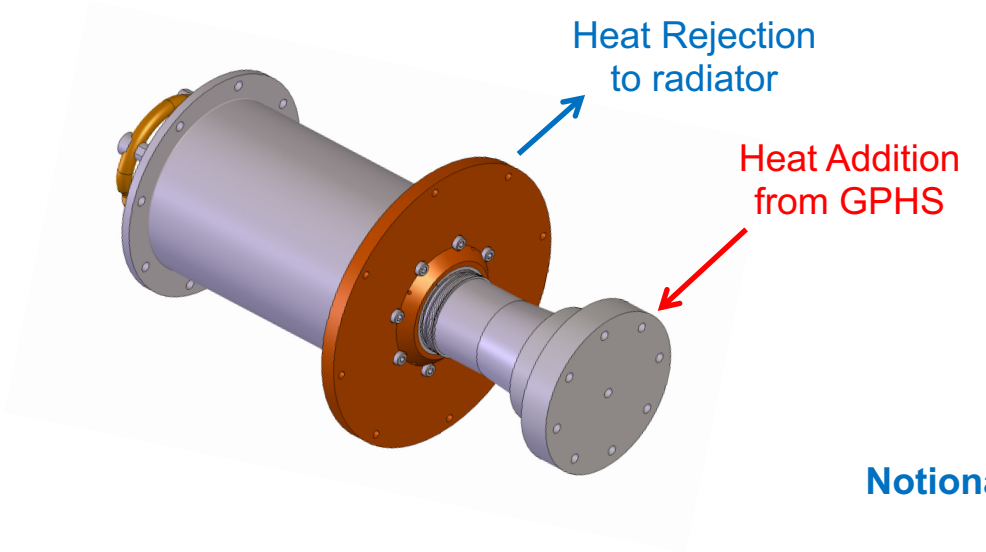
Notional 337 W generator concept with 100% convertor redundancy (1 required, 2 installed, 6 GPHS's)

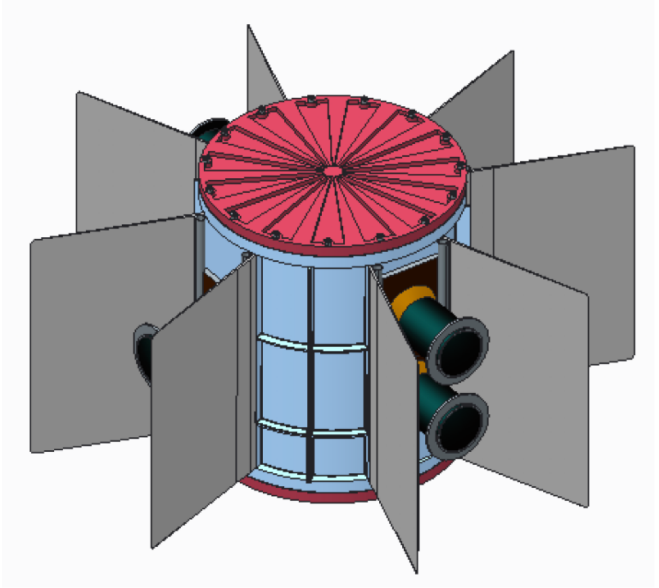
Design Parameters

Turbine Inlet Temp (Hot-end)	730 °C
Compressor Inlet Temp (Tcold)	20 to 175 °C
Efficiency	26% @ T_{COLD}=100°C
Power Output	337 W_{ac}
Mass	16.5 kg (>20W_e/kg)

- Closed Brayton continuous flow cycle with recuperation to achieve high efficiency
- Scaled-down from previous designs
- Leverages heritage from Creare's Hubble Space Telescope NICMOS cooler
- Two counter-rotating units permits redundancy, and nullifies angular momentum

Sunpower Robust Stirling Convertor (SRSC)





Notional 255 W generator concept with 50% convertor redundancy (4 required, 6 installed, 4 GPHS's)

Design Parameters

Hot-end Temp	640°C
Cold-end Temp	20 to 175 °C
Efficiency	30% @ T_{COLD}=100°C
Power Output	64 W_{ac}
Mass	1.6 kg (> 20 W_e/kg)

- Gas-bearing based free-piston Stirling convertor
- Derivative of Advanced Stirling Convertor (ASC) from ASRG Project
- **Design deltas relative to ASC to improve the following:**
  - Higher radial gas bearing load capacity, higher cold-end temperature capability
  - Regenerator robustness improvements, debris tolerance
  - Overstroke tolerance, passive collision prevention system, bumpers, encapsulated magnets

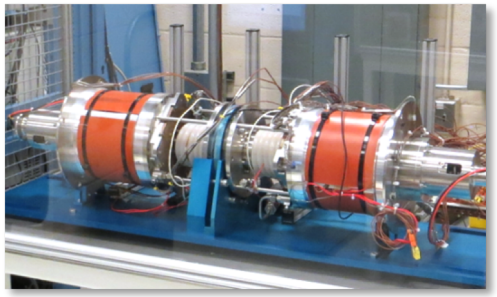
Prototype Testing and Analysis

- **Phase I - Complete**
  - Analysis completed to determine margin (against requirements and for hot thin-walled pressure barriers, joint analysis, temperature limits for various materials, etc.)
- **Phase II – In progress (~50% complete)**
  - Beginning of phase for final analysis for any revised features, production readiness
  - Prototype fabrication
  - Test prior to delivery (required temperatures, 50% heat input, start/stop, temporary loss of load)
- **Phase III – Next**
  - **Government IV&V Testing**

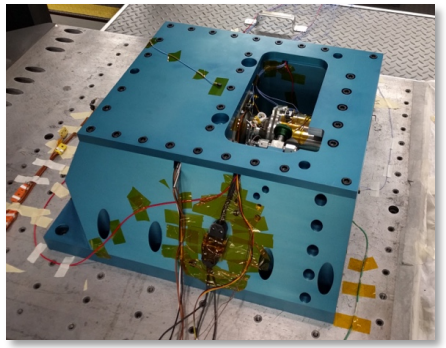
Independent Validation & Verification Testing

- **Demonstrate robustness to critical environments**
  - Ground operations
    - Horizontal orientation in different quadrants
    - Start/stop cycling
    - Thermal cycling
    - Steady operation
  - Random vibration simulates launch environment
  - Constant acceleration
    - Simulates potential spin stabilization for short period (days)
    - Simulates spacecraft entry into an atmosphere (entry, decent, and landing or EDL)
- **Inspecting data and hardware to verify robustness**
  - Steady operation period before and after each critical test
  - Partial disassembly desired to enable inspection of running surfaces

Ground Operations

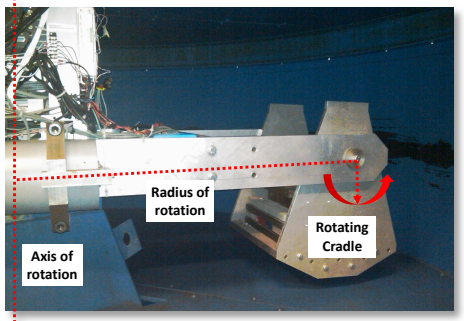


Launch System



Cruise

Spin Stabilization and EDL



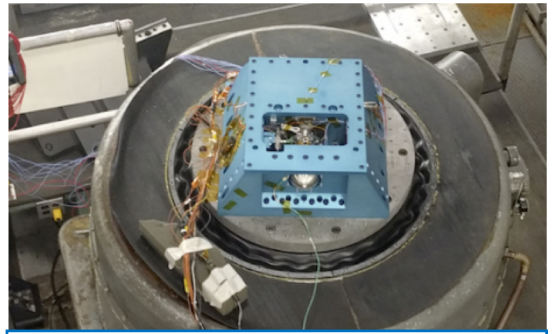
GRC Dynamic Power Test Facilities

- GRC's Stirling Research Laboratory (SRL)
  - Able to test dynamic convertors, controllers, and electrically heated generators
  - Unattended 24/7 operation to acquire life & reliability data, automated data collection and archiving, safety provisions for graceful shutdown in case of fault or power outage
  - **1,000,000 hours** of free-piston Stirling convertor operation achieved on October 24, 2018
  - Current record holder for longest operating free-piston Stirling convertor accumulated over 13.2 years of operation
  - Longest running free-piston Stirling convertor after launch vibration has accumulated 9.1 years of operation
  - Longest running free-piston Stirling convertor on engineering unit controller accumulated 4.9 years of operation
- Dedicated thermal vacuum facility for relevant environment tests
  - Over 25,000 hours of convertor operation in vacuum
- Performs tactical and durability tests for IV&V

Generator Extended Operation

Performance Testing & Extended Operation

Centrifuge Test Facility at CWRU



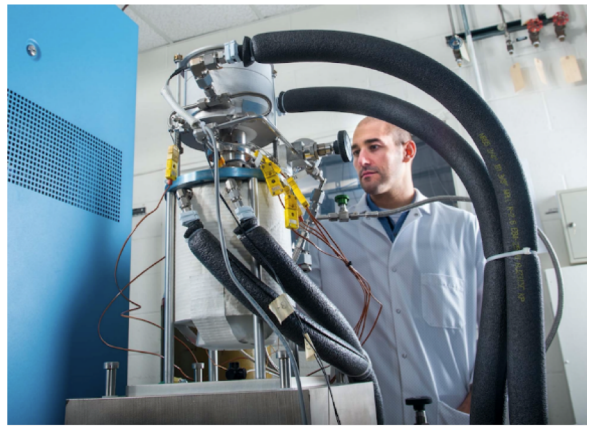
Vibe Testing at GRC Structural Dynamics Laboratory

Stirling Convertor Extended Operation

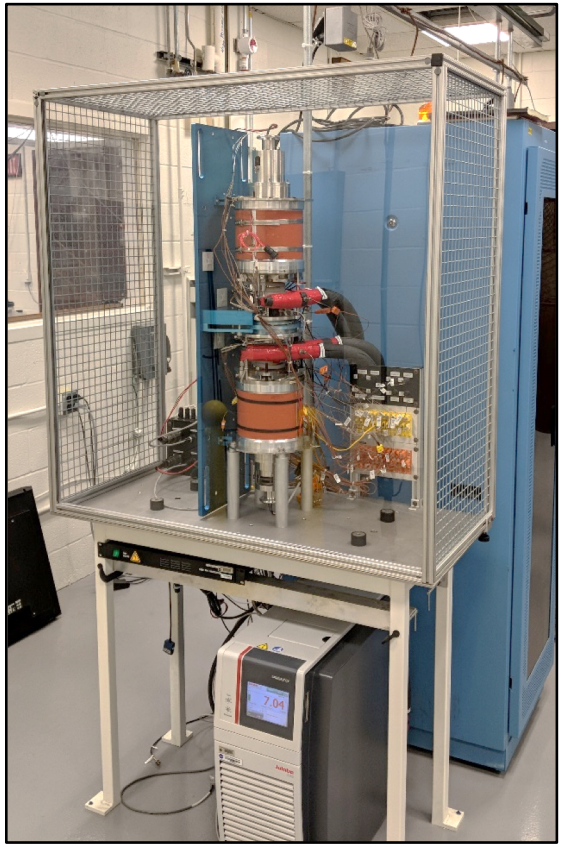
- Currently 12 convertors are on extended operation testing in the GRC SRL
- **TDC #13 started operation in June 2003 and is the longest running Stirling convertor**

Project & Provider	Test Article	Hrs of Operation
SRG 110 Infinia, Corp.	**TDC #13**	**116,058 (13.2 yrs)**
	TDC #15 & #16	**108,212 each**
	SES #2* (SRG-110 eng unit)	**8,820**
ASRG Sunpower, Inc.	**ASC-E3 #4* , #9**	**34,210 / 20,253**
	ASC-E3 #6* , #8	**27,035 / 22,887**
	ASC-0 #3*	**79,284 (9.1 yrs)**
	ASC-L*	**42,492 (4.9 yrs)**

Cumulative Per-Convertor Runtime as of Feb 24, 2019
*Have undergone random vibe
(20 years = 175,000 hrs)



TDC #13 Extended Operation

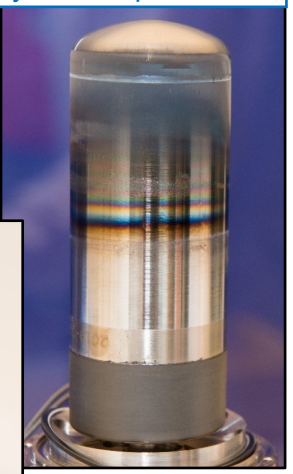


ASC-E3 Pair Extended Operation Test Article

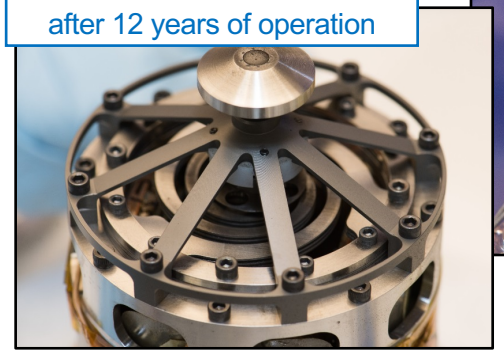
Recent Hardware Assessments

- **TDC #14 inspection after 105,620 hrs of operation (12 years)**
  - No sign of flexure degradation
  - Signs of oxidation on expected surfaces – likely from early non-hermetic operation
  - Geometric stability verified via Coordinate Measuring Machine (CMM)
  - Evidence of oxide residue/dust in various areas – did not degrade functionality of alternator or flexure bearings
- **Random Vibration & Centrifuge Testing of SES #2**
  - Engineering Unit convertor from SRG-110 project successfully passed launch simulation and constant acceleration while operating
  - **Vibration testing**: 10.35 grms profile formulated by SMT, encompasses wide span of launch vehicles, 2 min duration at full random vibe level
    - » Reduce piston amplitude for axial exposure (expected), temporary reduction in power output during lateral axes exposures (expected)
  - **Centrifuge testing**: Static acceleration exposure up to 5g axial and 20g lateral successfully completed in April 2018
  - SES #2 now operating continuously at full power, 8,820 hrs accumulated

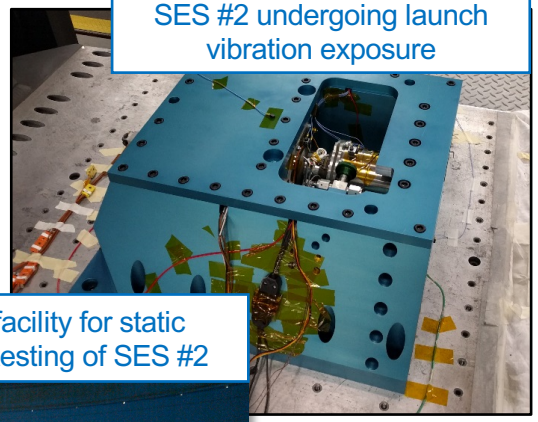
TDC #14 displacer after 12 years of operation



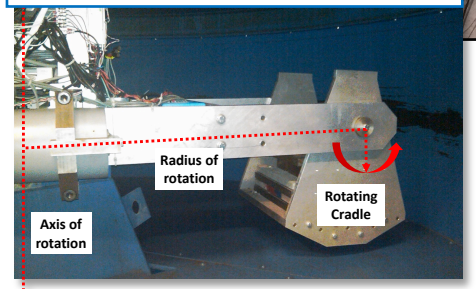
TDC #14 aft flexure stack after 12 years of operation



SES #2 undergoing launch vibration exposure



Centrifuge facility for static acceleration testing of SES #2



Conclusion

- DPC contracts started in late 2017 and are about half way through Phase 2 now
- Fabrication is in progress and first operation is anticipated in late summer
- Contracts have resulted in promising designs thus far
- Research continues at NASA GRC utilizing existing hardware to identify relevant risks
- NASA GRC is preparing for DPC prototype IV&V testing in 2020
- Dynamic Power Convertor for RPS
  - **SMT identified requirements**
  - **Contracts being used to develop conversion technologies**
  - **Government IV&V testing will verify prototypes meet requirements**
  - **Decision Gate 2 could result in recommendation for flight development**

Special thanks to:

- **RPS Program and DRPS Project**
- **Stirling Research Laboratory Team**

Thank you for attending