National Aeronautics and Space Administration

Dynamic Power Convertor Development for Radioisotope Power Systems at NASA GRC

AIAA Power and Energy Forum

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Salvatore Oriti, Scott Wilson

NASA Glenn Research Center

Thermal Energy Conversion Branch

Dynamic-Conversion Power System Background

Advantages:
- Higher thermal-to-electric efficiency (up to 40%)
- Lower waste heat to output power ratio
- Low generator power decline (fuel decay only)
- Large multi-mission generator design space
- Extensible to high power levels

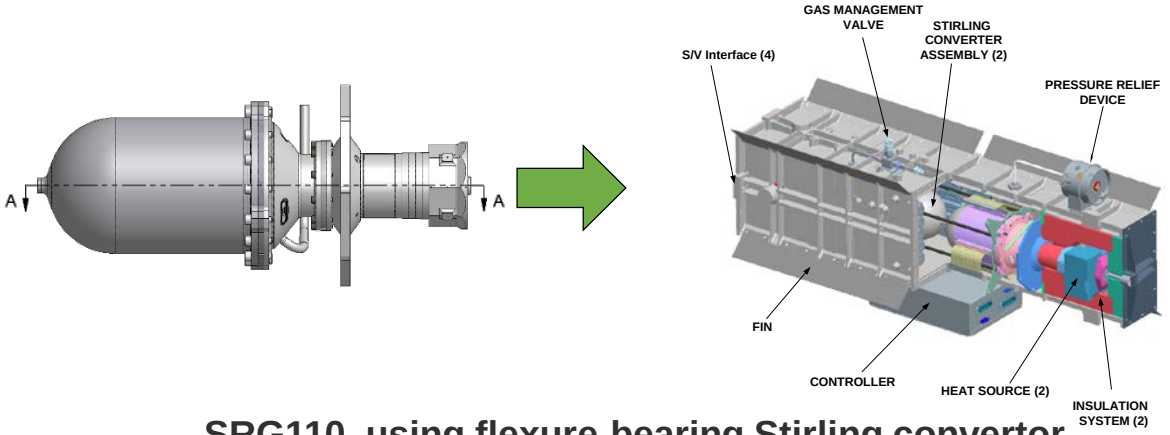
SRG-110

- ~114 W_e output
- Infinia's Technology Demonstration Convertor (TDC)
- 2 Pu-238 GPHS modules
- Overall efficiency = 23%
- 4.2 W_e/kg (before engineering unit build)
- Developed during 2001 to 2006 timeframe

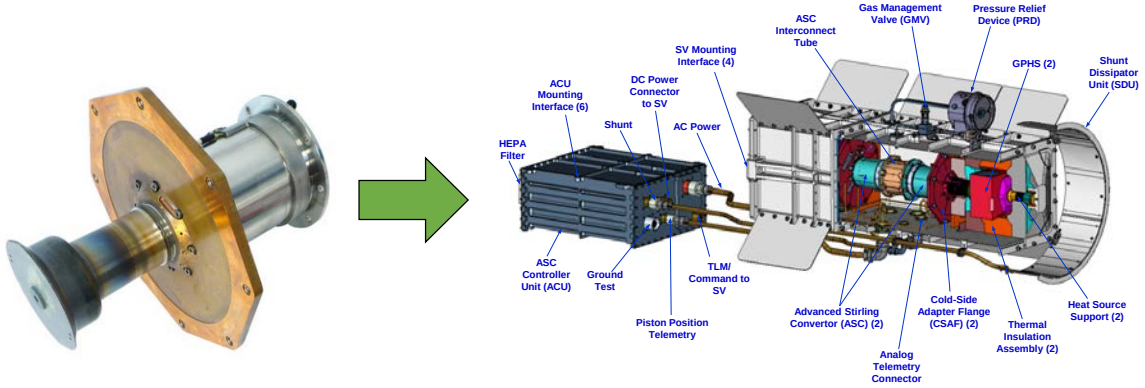
ASRG

- ~140 W_e output
- Sunpower's Advanced Stirling Convertor (ASC)
- 2 GPHS modules
- Overall efficiency = 28%
- 4.4 W_e/kg
- Developed during 2006 to 2013 timeframe

Convertor **Generator**



SRG110, using flexure-bearing Stirling convertor
(image credit : Lockheed Martin)

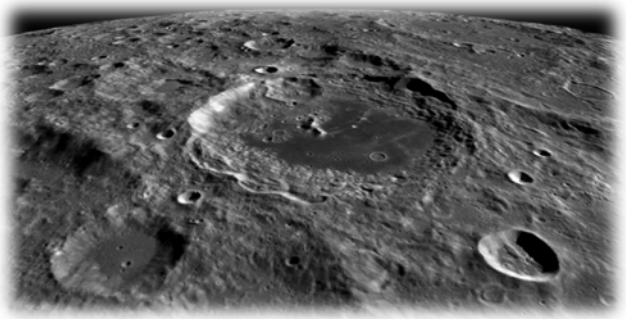


ASRG, using gas-bearing Stirling convertor
(image credits : Sunpower, Lockheed Martin)

Convertor Performance Goals

Item	Description
Life	20 years
Efficiency	≥ 24% at T_{cold} > 100 °C
Specific Power	≥ 20 W_e/kg (convertor only)
Partial power	Can be throttled down to 50%
Degradation	< 0.5% / year
Hot-End Temp	< 1000 °C
Cold-End Temp	20 to 175 °C
Random Vibe	Launch qual
Static Accel	20g for 1 minute, 5g for 5 days
Radiation	300 krad
Size	Enables generator that can fit in DOE shipping container

Applicable to wide range of missions



Lunar
(Far side & South Aitken Basin)

Europa

Titan

Robustness goals also defined:

- Design has margin to tolerate events outside expected environments
- Fewer single-point-failures is more robust
- Tolerant of loss of electrical load
- Tolerant of operational error
- Manufacturability not dependent on specialized workmanship

Convertor Development Timeline

Status	Date	Description
✓	2016-Aug	RFP Release
✓	2016-Nov	Proposal review
✓	2017-Jul	Contract awards (4)
✓	2017-2018	Phase 1 - Design
✓	2018-Apr	Decision Gate 1
Ongoing	2018-2020	Phase 2 – Fab & Test
Future	2020-2021	Phase 3 – IV&V
Future	2021	Decision Gate 2
Future	2021	Goal : Begin DOE flight generator development

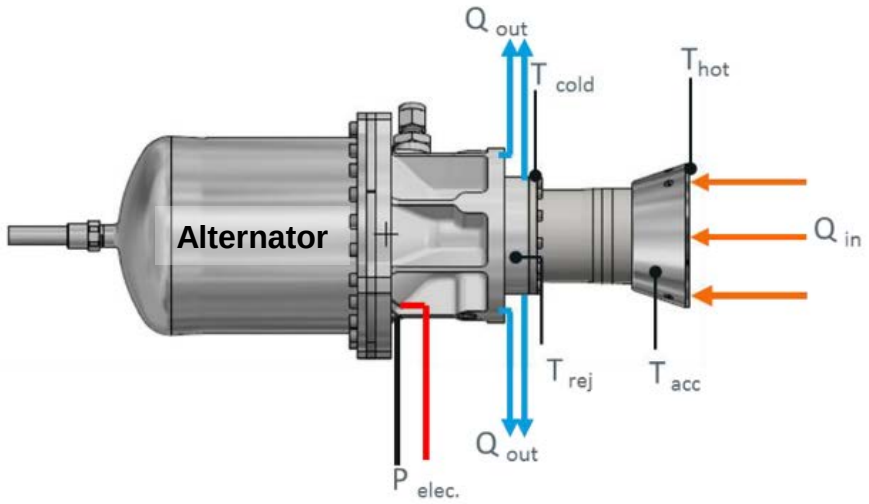
Convertor development contracts awarded in 2017:

Item	Units	Flexure Isotope Stirling Convertor (FISC) American Superconductor, Inc.	Turbo-Brayton Convertor (TBC) Creare, LLC	Thermo-Acoustic Power Convertor (TAPC) Northrop Grumman	Sunpower Robust Stirling Convertor (SRSC) Sunpower, Inc.
Power	W_e	70	355	110	65
Efficiency	%	31	26	26	29
Hot-end Temp	°C	650	730	700	720
Mass	kg	3.3	15.5	6.4	2.0
Specific Power	W_e/kg	21	22	17	33

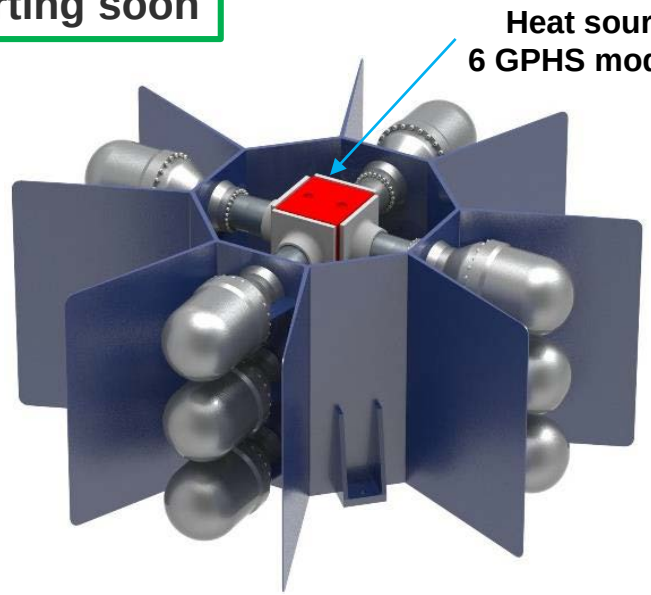
Flexure Isotope Stirling Convertor (FISC)

American SuperConductor (AMSC), formerly Infinia Tech Corp.

Phase 2 awarded : 2018-April
Component fabrication starting soon



70 W Flexure Isotope Stirling Convertor (FISC)



Notional 420 W_e generator concept with 100% convertor redundancy

FISC Characteristics

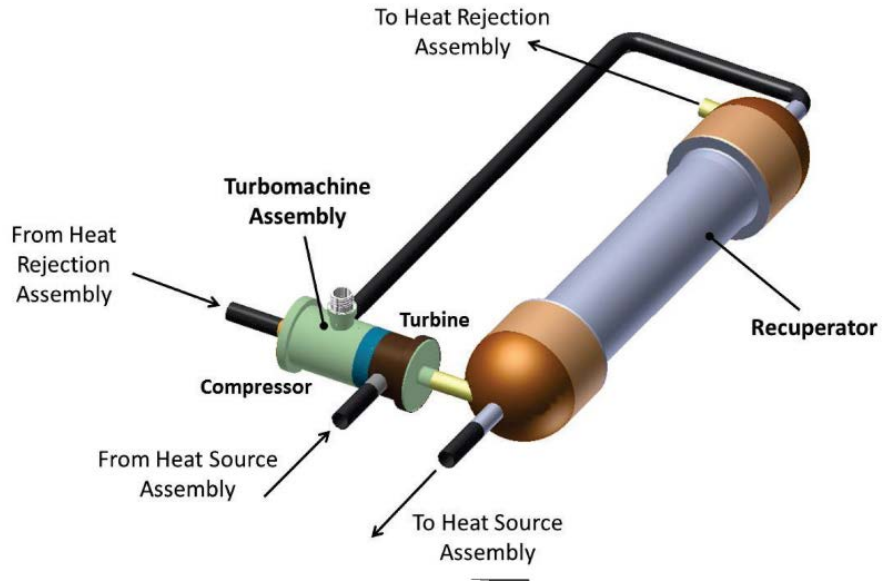
Power Output	**70 W_e**
Efficiency	**31% @ T_{COLD}=100°C**
Fraction of Carnot	**0.52**
Hot-end Temp	**650 °C**
Mass	**3.3 kg (~21W_e/kg)**

- **Flexure-bearings, beta arrangement free-piston Stirling convertor**
- **Derivative of Technology Demonstration Convertor (TDC) from SRG-110 project**
- **TDCs have established long operational life via convertor testing at GRC**
- **Design deltas relative to TDC to improve the following:**
  1. Higher radial stiffness flexures, overstroke tolerance, hot-end temperature margin
  2. Independently verifiable subassemblies
  3. Higher efficiency alternator, higher cold-end temp capability
  4. System integration : Tailored interfaces

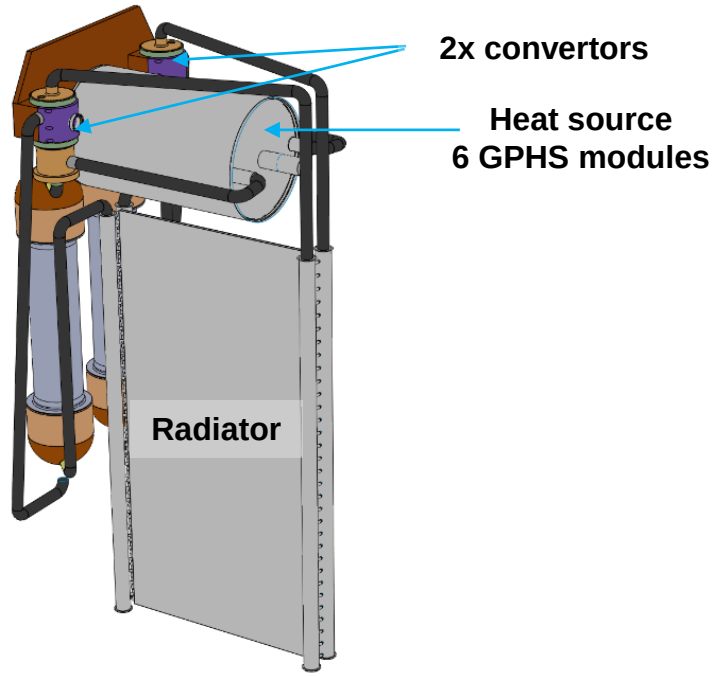
Turbo-Brayton Convertor (TBC)

Creare, LLC

Phase 2 awarded : 2018-April
Component fabrication has begun



355 W_e Turbo-Brayton Convertor (TBC)



Notional 355 W_e generator concept with 100% convertor redundancy

TBC Characteristics

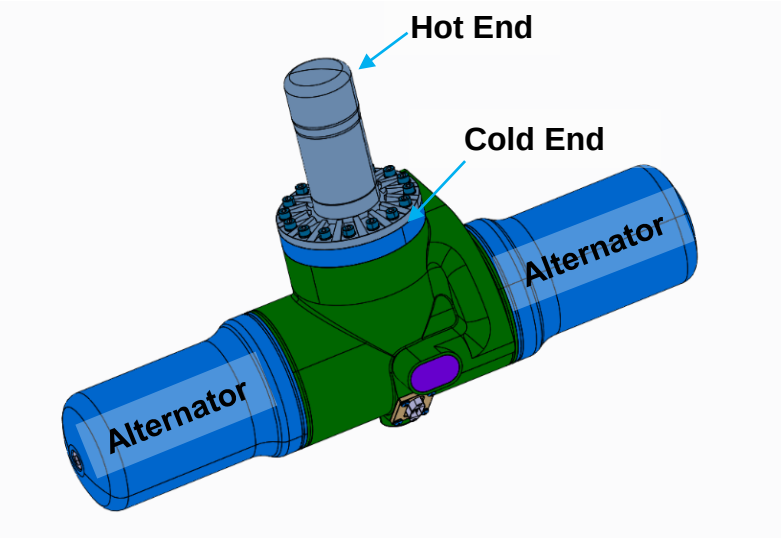
Power Output	355 W_e
Efficiency	26% @ T_{COLD}=100°C
Fraction of Carnot	0.41
Turbine Inlet Temp	730 °C
Mass	15.5 kg (22 W_e/kg)

- Closed Brayton continuous flow cycle with recuperation
- Scaled-down from previous designs
- Life-limiting engineering : Hot-end material creep from centrifugal stress
- Recuperator is large portion of convertor mass
- Two counter-rotating units permits redundancy, and nullifies angular momentum
- Flexible component placement on spacecraft

Thermo-Acoustic Power Convertor (TAPC)

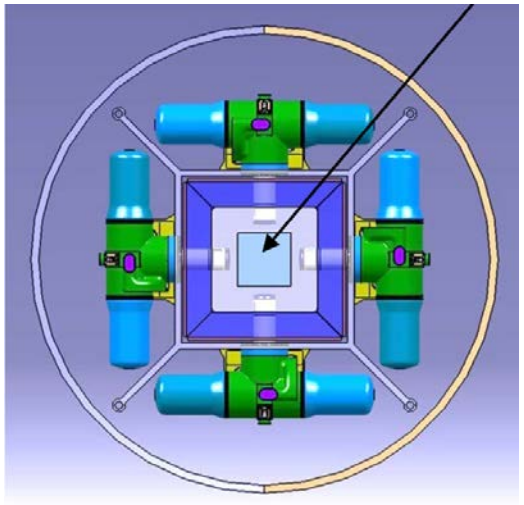
Northrop Grumman Aerospace Systems

Phase 1 : Complete
Phase 2 will not be awarded



110 W_e Thermo-Acoustic Power Convertor (TAPC)

GPHS modules



Notional 220 W_e generator concept with 100% convertor redundancy

TAPC Characteristics

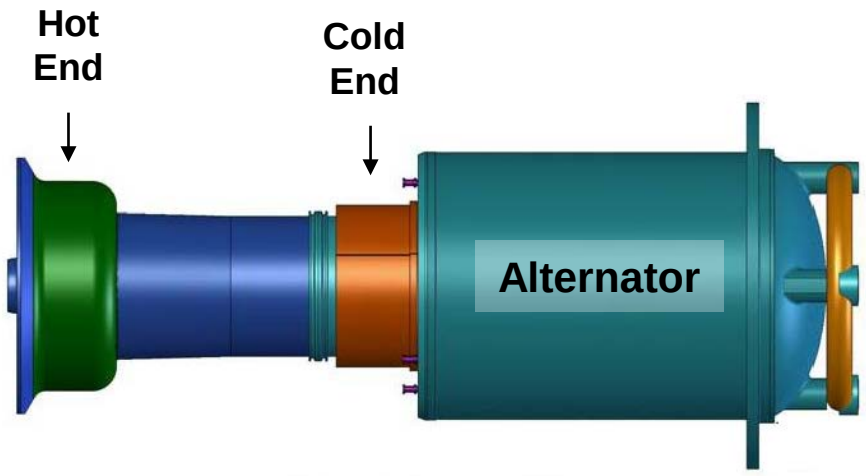
Power Output	**110 W_e**
Efficiency	**26% @ T_{COLD}=100°C**
Fraction of Carnot	**0.42**
Hot-End Temp	**700 °C**
Mass	**6.4 kg (17 W_e/kg)**

- **Thermoacoustic Stirling cycle**
- **Eliminates physical displacer (no moving parts in hot end)**
- **Natively balanced, dual-opposed alternator building block**
- **Alternators driven by shared compression space**
- **Based on previous development efforts:**
  2003 NRA, IRAD-developed device

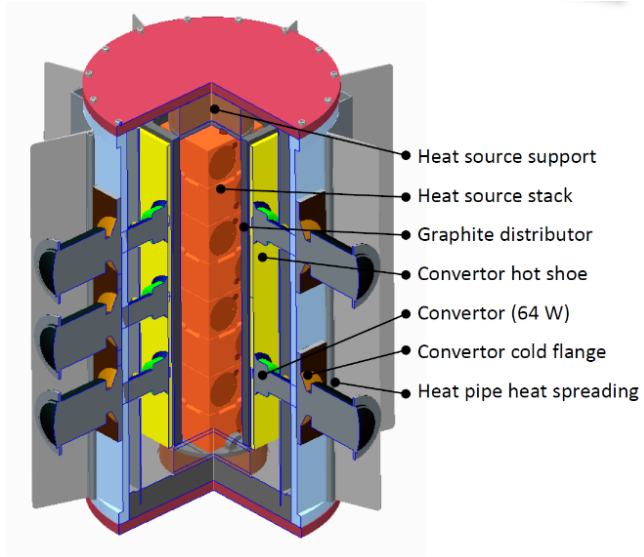
Sunpower Robust Stirling Convertor (SRSC)

Sunpower, Inc.

Phase 1 : Complete
Phase 2 award in process



65 W_e Sunpower Robust Stirling Convertor (SRSC)



Notional 500 W_e generator concept with 25% convertor redundancy

SRSC Characteristics

Power Output	**65W_e**
Efficiency	**29% @ T_{COLD}=100°C**
Fraction of Carnot	**0.46**
Hot-End Temp	**720 °C**
Mass	**2.0 kg (33 W_e/kg)**

- **Gas-bearing based, beta arrangement free-piston Stirling convertor**
- **Derivative of Advanced Stirling Convertor (ASC) from ASRG Project**
- **Enables wide generator design space**
- **Design deltas relative to ASC to improve the following:**

1. Higher radial gas bearing stiffness, overstroke tolerance
2. Regenerator robustness, debris tolerance
3. Higher cold-end temp and static acceleration capability

Path to Flight

Goal:

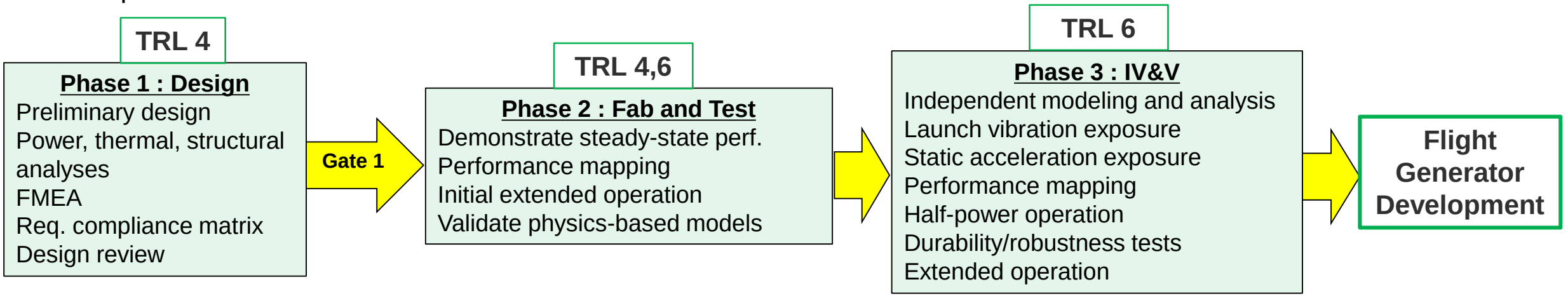
Achieve convertor TRL 6, then initiate generator flight development

NASA definition of TRL 6: “System/subsystem model or prototype demonstration in a relevant environment (ground or space)”

Relevant environments can be simulated

Surrogate Mission Team (SMT), chartered by RPS Program

- NASA, DOE, JPL, APL, GSFC
- Formulated requirements to provide mission pull
- Integrated with convertor contract progress monitoring
- Formulated a TRL evaluation method
- Providing failure mode and probability of success analysis
- Work phases and deliverables tied to TRL advancement

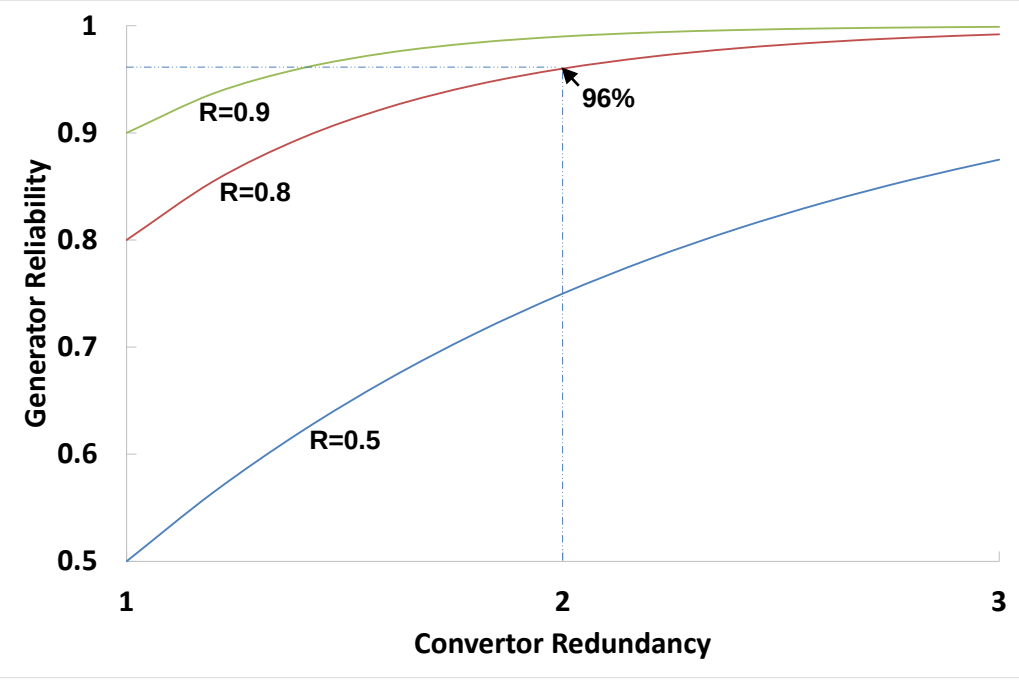


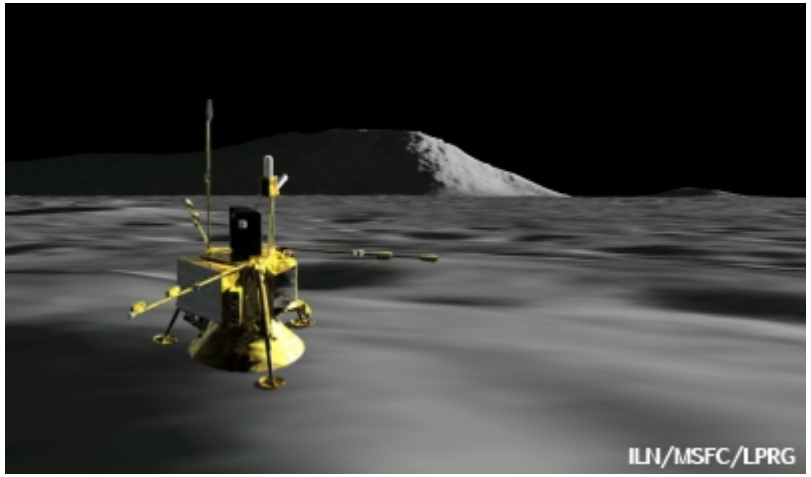
First Mission Potential

First flight-mission use of any new conversion technology must accept some risk

20 year life requirement is atypical

- Demonstrating 2x life via experiment is not realistic
- Statistical reliability analysis will have small number of hardware data points
- Fabrication of tens of hardware data points not possible on current timeline
- Convertor-level accelerated testing not possible
- Convertor component accelerated testing is possible
- Convertor redundancy has significant effect on generator reliability





Lunar mission is an attractive first use

- Short cruise time (days, not years)
- Short mission duration (2 years instead of 20)
- Significant science return
- Many candidate missions enabled or enhanced by nuclear power

Stirling Convertor Reliability Demonstrations

NASA GRC has demonstrated zero-degradation long-term operation of several flight-relevant convertors

Project & Provider	Test Article	Bearing Technology	Years of Operation	Status
SRG-110 Infinia, Corp.	**TDC #13**[1]	**Flexure**	12.6	On-going
	TDC #14		12.1	Shutdown for disassembly and inspection
	TDC #15		11.6	On-going
	TDC #16		11.6	On-going
	SES #2[2]		0.3	On-going
ASRG Sunpower, Inc.	**ASC-0 #3**[2]	**Gas**	8.3	On-going
	ASC-E3 #3		2.5	Shutdown for disassembly and inspection
	ASC-E3 #4[2]		3.1	On-going
	ASC-E3 #6[2]		2.4	On-going
	ASC-E3 #8		1.9	On-going
	ASC-E3 #9		1.6	On-going
	ASC-L[2]		4.0	On-going

Cumulative Per-Convertor Runtime as of June 2018

[1]Current record-holder for maintenance-free heat engine runtime

[2]Have undergone random vibe portion of life certification

TDC #14 disassembled and inspected after 12 years of operation:

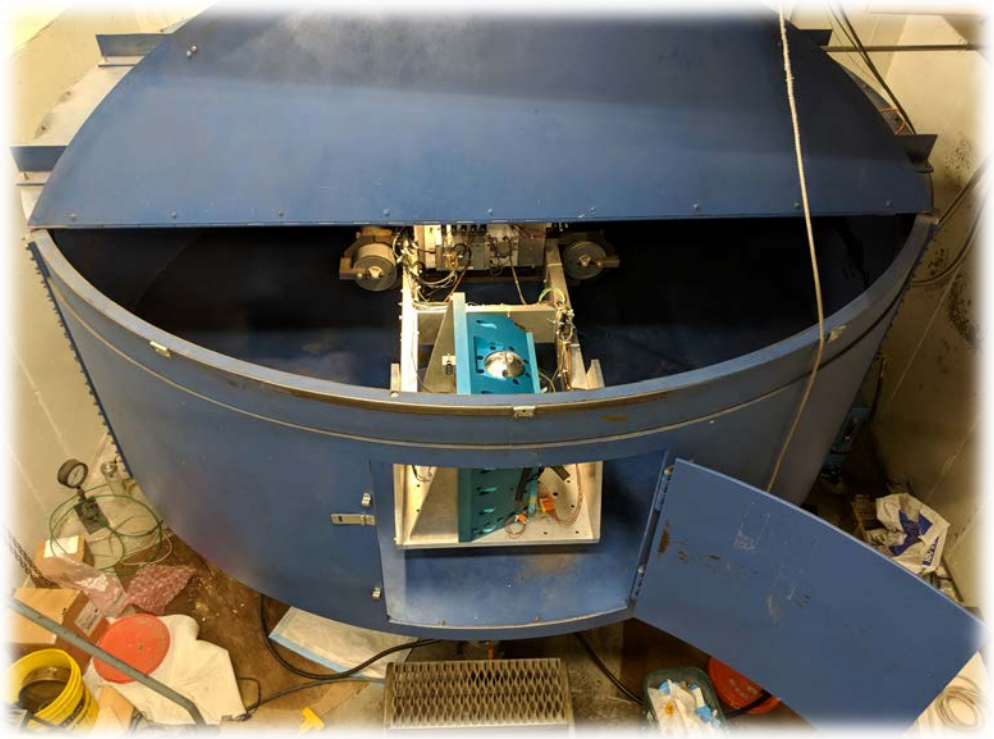
- No evidence of degradation
- Robustness demonstrated
- Tolerated debris, oxygen ingress, and overstroke
- Further disassembly commencing
- Will enable inspection of regenerator and flexure bearings
- ASC-E3 #3 will also be disassembled

TDC #13 extended operation setup

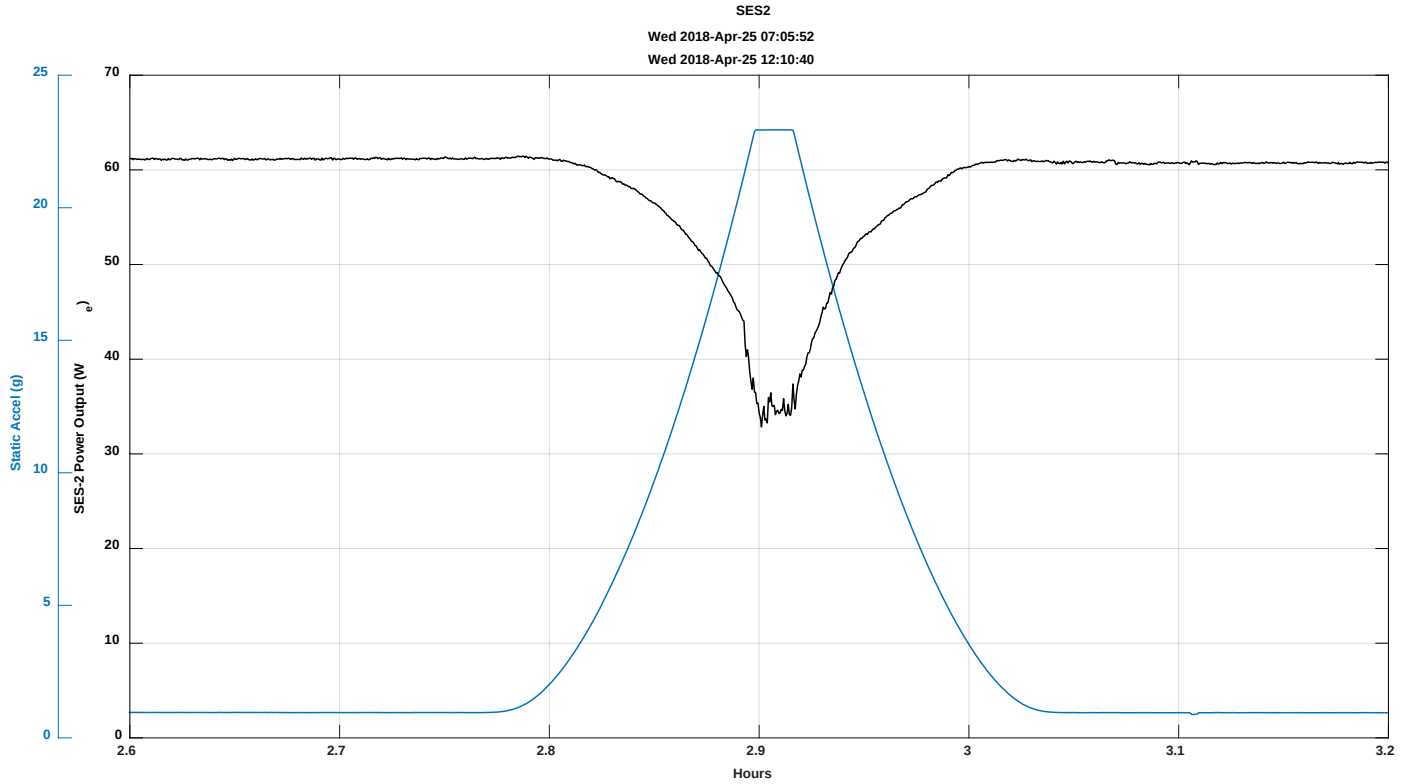
ASC-E3 Pair Extended Operation Test Article

Static Acceleration Exposure

NASA GRC recently characterized flexure-bearing convertor under static acceleration environment (20g for 1 minute)



SES #2 setup in centrifuge for static acceleration exposure to 20g



Results : Temporary reduction in convertor power output
Convertor returned to extended operation to track long-term performance

Conclusions and Next Steps

NASA's dynamic power convertor development in support of high-efficiency RPS is progressing as planned, and shows promise

- **3 DPC contracts have passed Decision Gate 1, and have been awarded Phase 2 (convertor prototype fabrication and test)**
- **NASA GRC is preparing for DPC prototype IV&V, ~2020**
- **Ongoing research utilizing existing hardware supports viability of dynamic power conversion for RPS**
- **Next steps:**
  1. Finalize convertor IV&V plan
  2. Burn down risks
  3. Develop generator development path