

# Dynamic Power Converter Development for Radioisotope Power Systems at NASA GRC

AIAA Power and Energy Forum

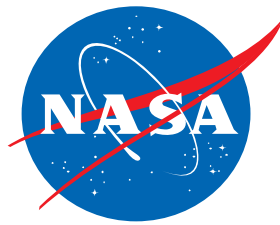
July 9, 2018

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NASA Glenn Research Center

Thermal Energy Conversion Branch

# Dynamic-Conversion Power System Background



## Advantages:

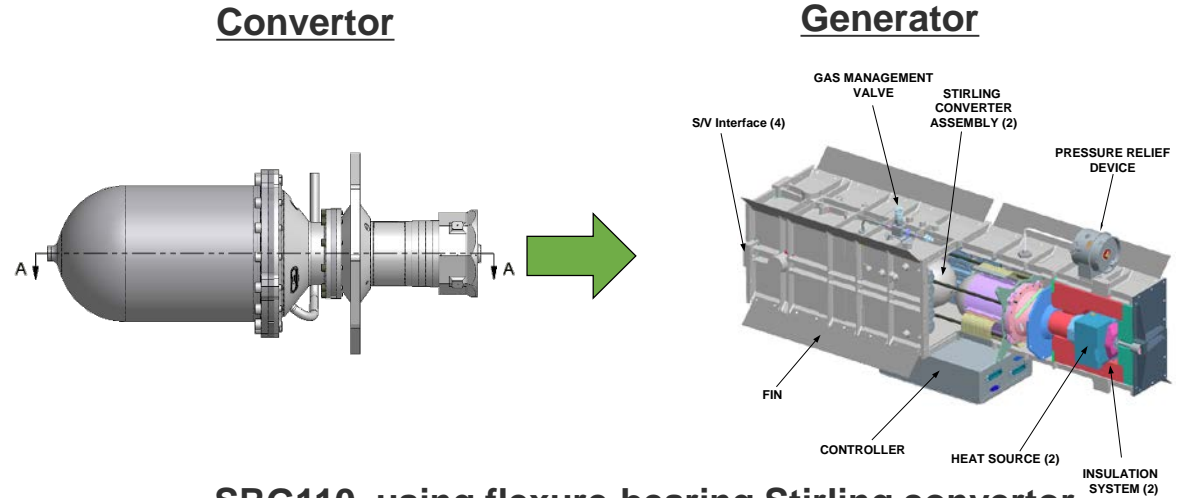
- Higher thermal-to-electric efficiency (up to 40%)
- Lower waste heat to output power ratio
- Low generator power decline (fuel decay only)
- Large multi-mission generator design space
- Extensible to high power levels

## SRG-110

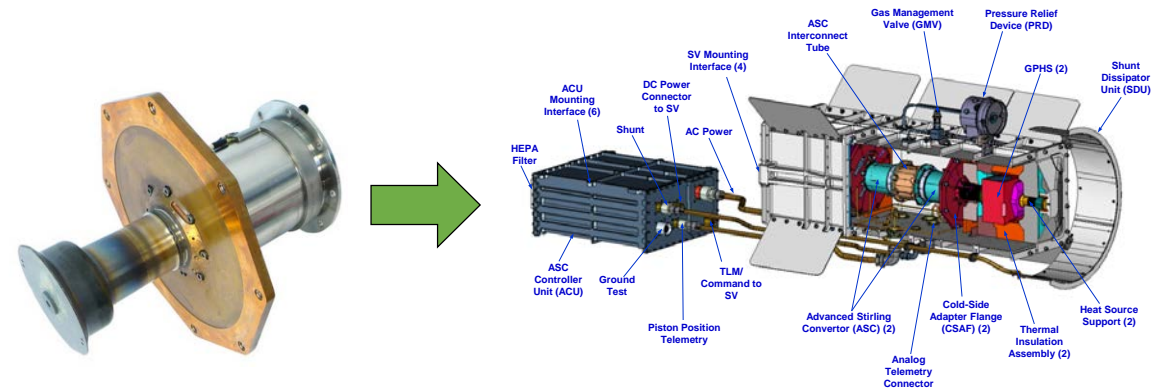
- ~114  $W_e$  output
- Infinia's Technology Demonstration Convertor (TDC)
- 2 Pu-238 GPHS modules
- Overall efficiency = 23%
- 4.2  $W_e/kg$  (before engineering unit build)
- Developed during 2001 to 2006 timeframe

## 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

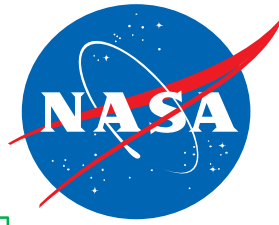


SRG110, using flexure-bearing Stirling convertor  
(image credit : Lockheed Martin)



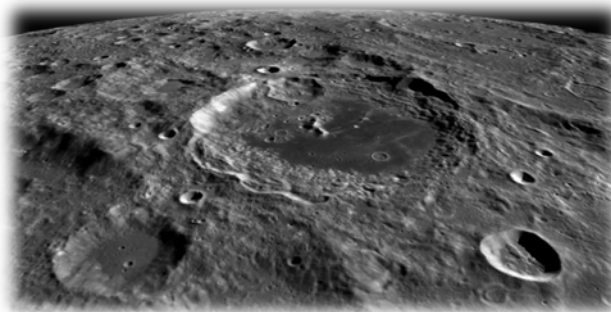
ASRG, using gas-bearing Stirling convertor  
(image credits : Sunpower, Lockheed Martin)

# Convertor Performance Goals



Item	Description
Life	20 years
Efficiency	$\geq 24\%$ at $T_{\text{cold}} > 100\text{ }^{\circ}\text{C}$
Specific Power	$\geq 20\text{ W}_e/\text{kg}$ (convertor only)
Partial power	Can be throttled down to 50%
Degradation	$< 0.5\%$ / year
Hot-End Temp	$< 1000\text{ }^{\circ}\text{C}$
Cold-End Temp	20 to $175\text{ }^{\circ}\text{C}$
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

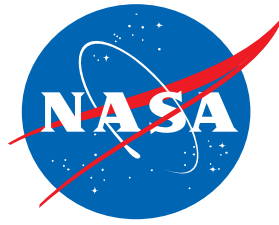


Titan

## 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

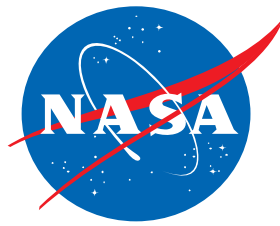
## Convertor development contracts awarded in 2017:

Item	Units	Flexure Isotope Stirling Convertor (FISC) American Superconductor, Inc.	Turbo-Brayton Convertor (TBC) Create, 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

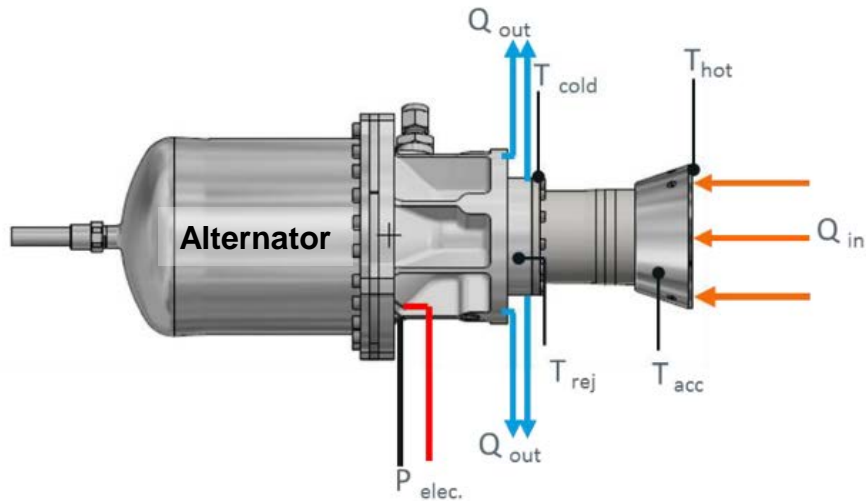


# Flexure Isotope Stirling Convertor (FISC)

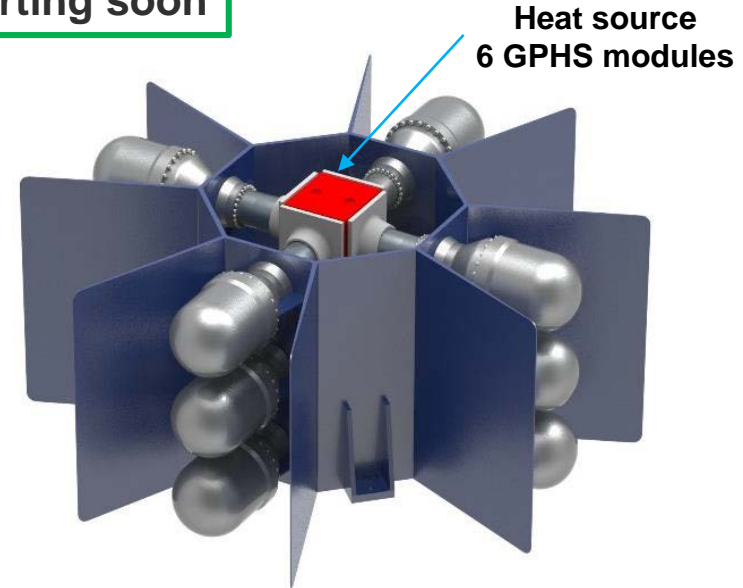
American SuperConductor (AMSC), formerly Infinia Tech Corp.



Phase 2 awarded : 2018-April  
Component fabrication starting soon



70 W Flexure Isotope Stirling Convertor (FISC)



Notional 420 W<sub>e</sub> generator concept with 100% convertor redundancy

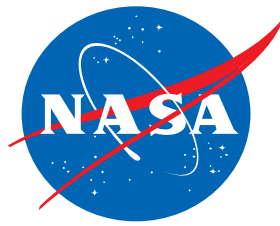
## FISC Characteristics

Power Output	70 W <sub>e</sub>
Efficiency	31% @ T <sub>COLD</sub> =100°C
Fraction of Carnot	0.52
Hot-end Temp	650 °C
Mass	3.3 kg (~21W <sub>e</sub> /kg)

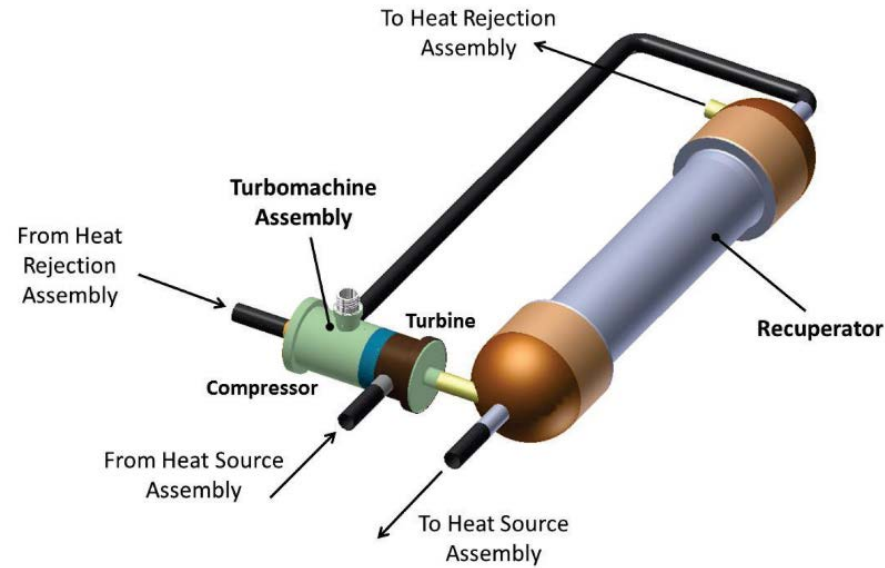
- Flexure-bearings, beta arrangement free-piston Stirling convertor
- Derivative of Technology Demonstration Convertor (TDC) from SRG-110 project
- TDCs have established long operational life via convertor testing at GRC
- Design deltas relative to TDC to improve the following:
  1. Higher radial stiffness 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)

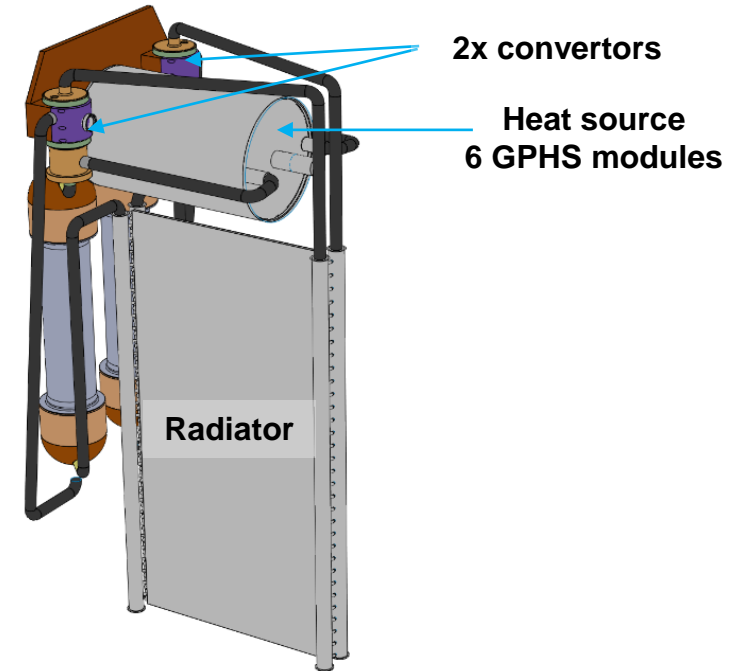
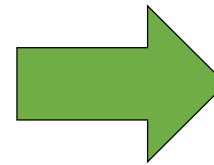
Creare, LLC



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

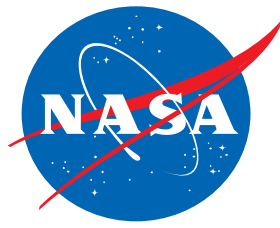
## TBC Characteristics

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

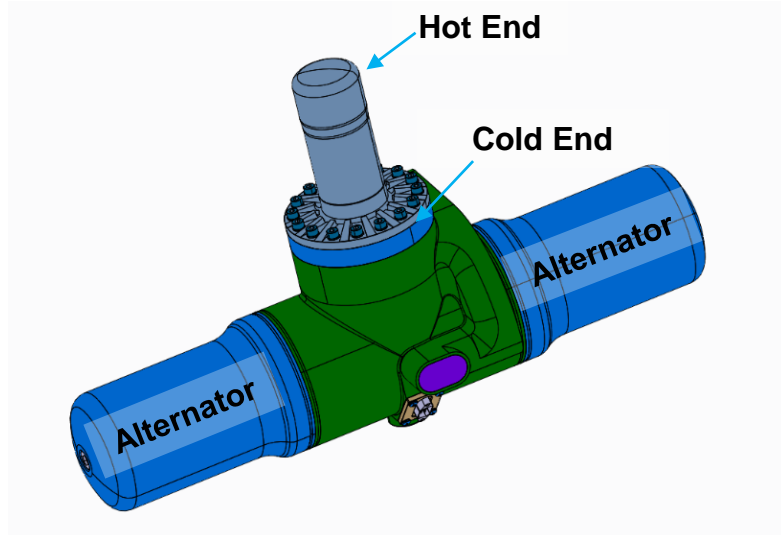
- Closed Brayton continuous flow cycle with recuperation
- Scaled-down from previous designs
- Life-limiting engineering : Hot-end material creep from centrifugal stress
- Recuperator is large portion of convertor mass
- Two counter-rotating units permits redundancy, and nullifies angular momentum
-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

# Thermo-Acoustic Power Converter (TAPC)

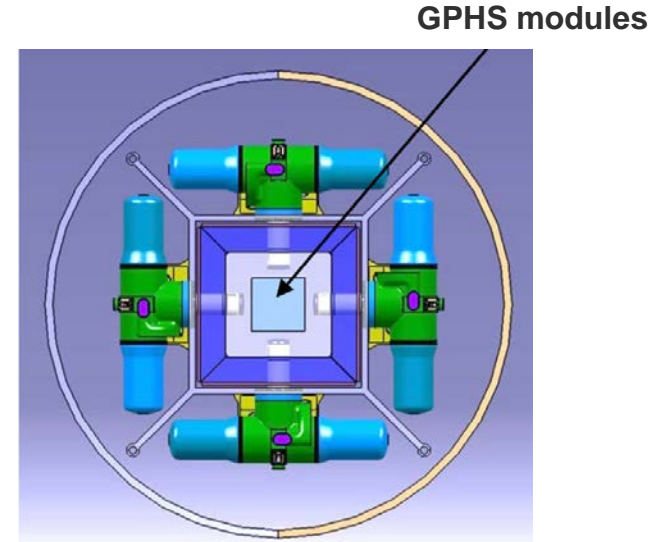
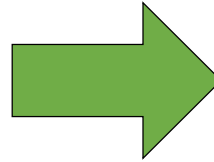
Northrop Grumman Aerospace Systems



Phase 1 : Complete  
Phase 2 will not be awarded



110  $W_e$  Thermo-Acoustic Power Converter (TAPC)



Notional 220  $W_e$  generator concept with 100% converter redundancy

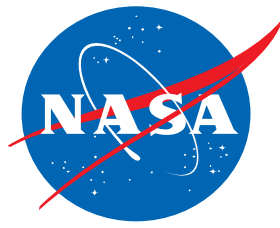
## TAPC Characteristics

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

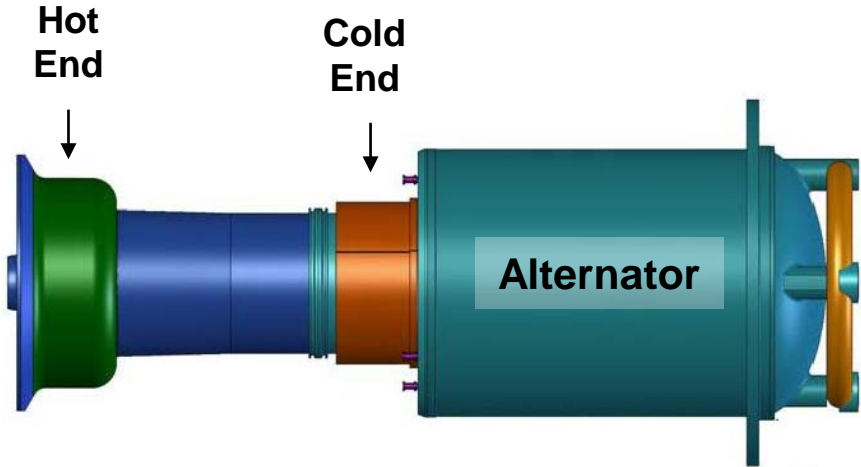
- Thermoacoustic Stirling cycle
- Eliminates physical displacer (no moving parts in hot end)
- Natively balanced, dual-opposed alternator building block
- Alternators driven by shared compression space
- Based on previous development efforts:  
2003 NRA, IRAD-developed device

# Sunpower Robust Stirling Converter (SRSC)

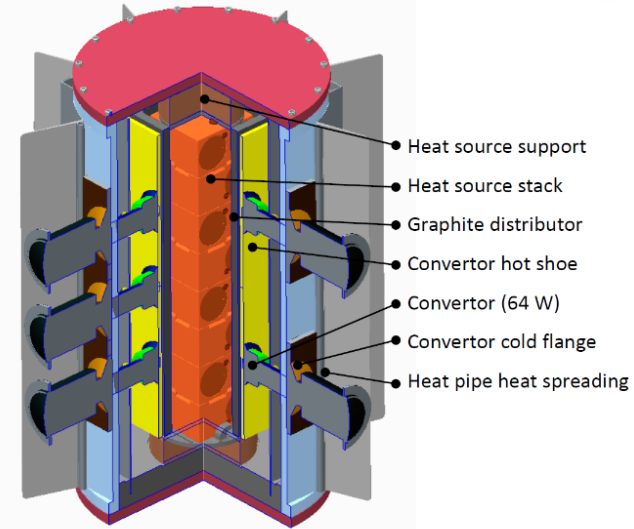
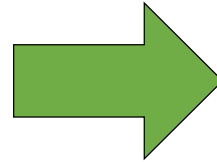
Sunpower, Inc.



Phase 1 : Complete  
Phase 2 award in process



65 W<sub>e</sub> Sunpower Robust Stirling Converter (SRSC)



Notional 500 W<sub>e</sub> generator concept with 25% convertor redundancy

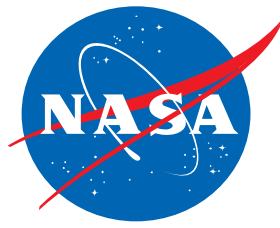
## SRSC Characteristics

Power Output	65W <sub>e</sub>
Efficiency	29% @ T <sub>COLD</sub> =100°C
Fraction of Carnot	0.46
Hot-End Temp	720 °C
Mass	2.0 kg (33 W <sub>e</sub> /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:

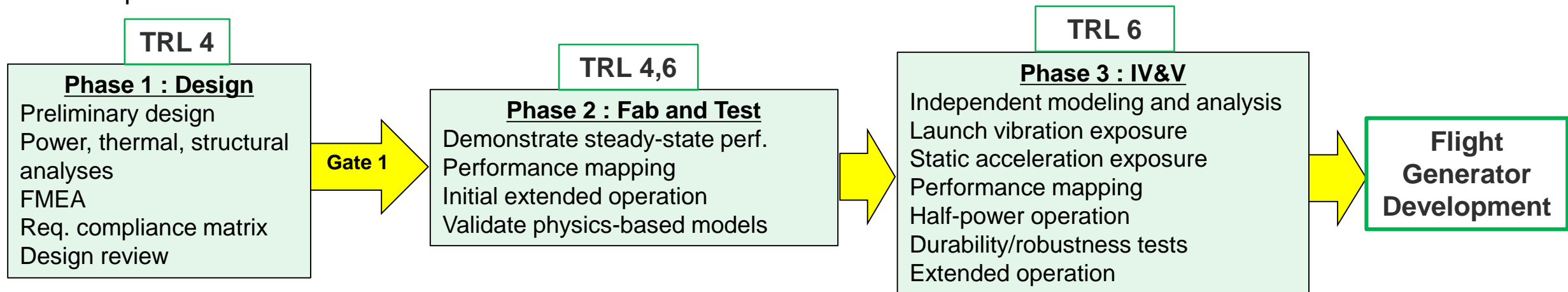
**Achieve convertor TRL 6, then initiate generator flight development**

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

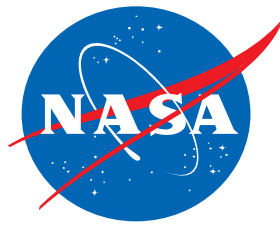
**Relevant environments can be simulated**

## 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



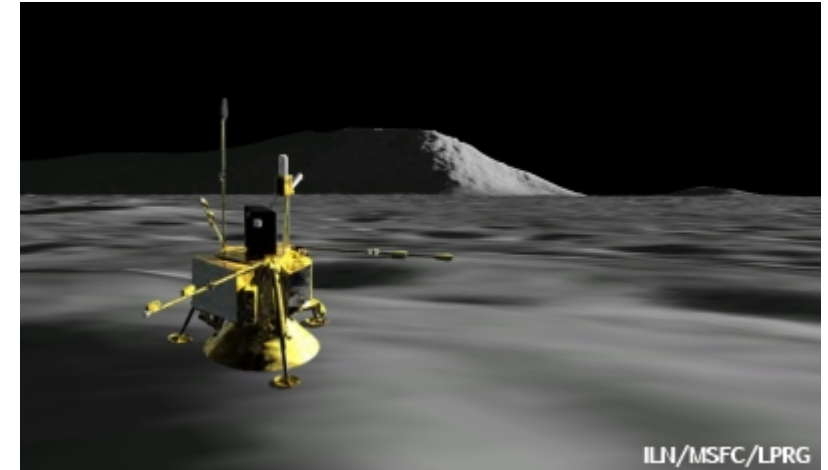
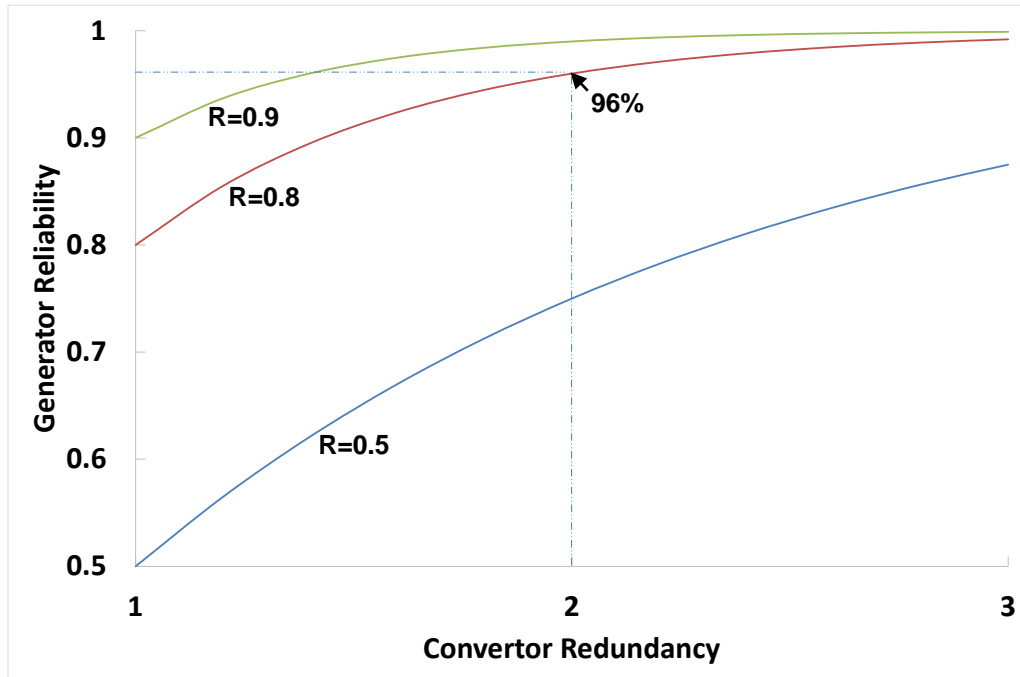
# First Mission Potential



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

## 20 year life requirement is atypical

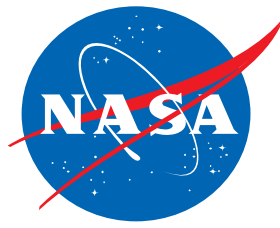
- Demonstrating 2x life via experiment is not realistic
- Statistical reliability analysis will have small number of hardware data points
- Fabrication of tens of hardware data points not possible on current timeline
- Converter-level accelerated testing not possible
- Converter component accelerated testing is possible
- Converter 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 <sup>1</sup>	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 <sup>2</sup>		0.3	On-going
ASRG Sunpower, Inc.	ASC-0 #3 <sup>2</sup>	Gas	8.3	On-going
	ASC-E3 #3		2.5	Shutdown for disassembly and inspection
	ASC-E3 #4 <sup>2</sup>		3.1	On-going
	ASC-E3 #6 <sup>2</sup>		2.4	On-going
	ASC-E3 #8		1.9	On-going
	ASC-E3 #9		1.6	On-going
	ASC-L <sup>2</sup>		4.0	On-going

### Cumulative Per-Convertor Runtime as of June 2018

<sup>1</sup>Current record-holder for maintenance-free heat engine runtime

<sup>2</sup>Have undergone random vibrate 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

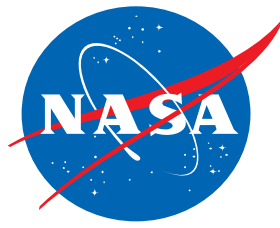


TDC #13 extended operation setup

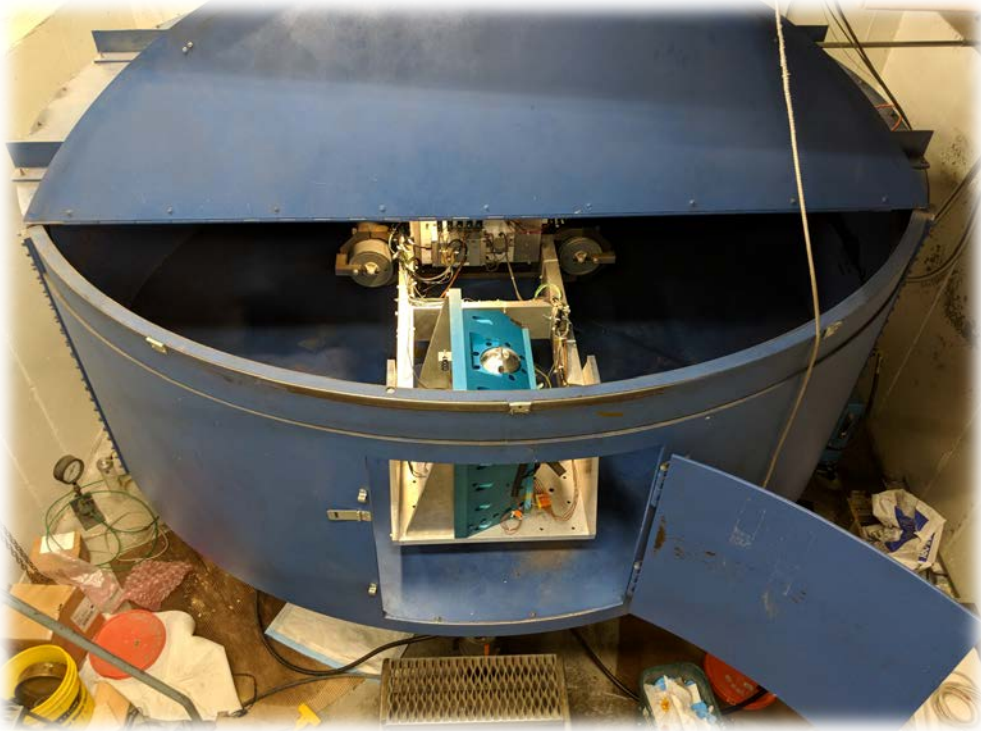


ASC-E3 Pair Extended Operation Test Article

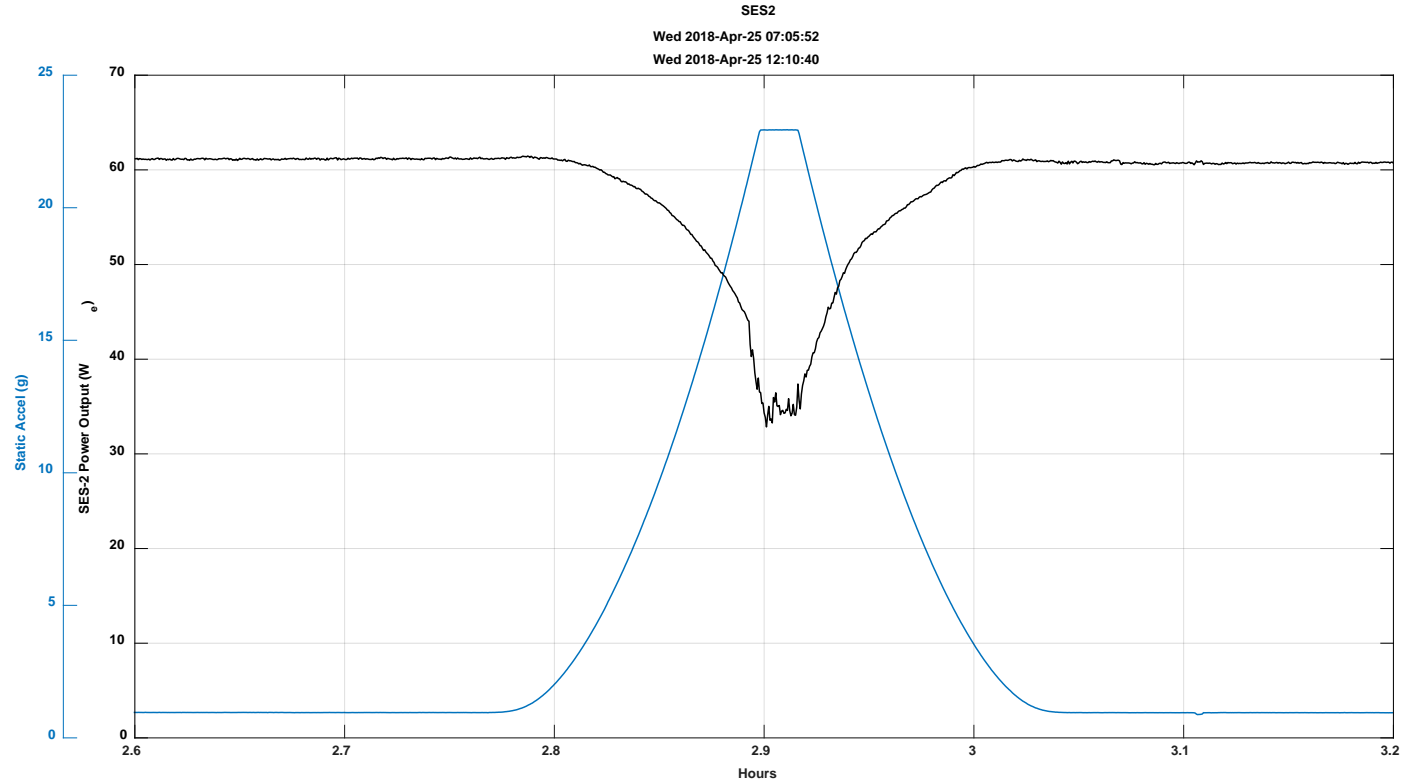
# Static Acceleration Exposure



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

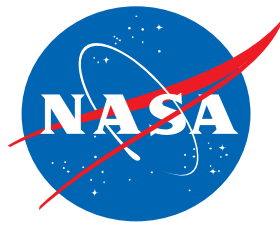


SES #2 setup in centrifuge for static acceleration exposure to 20g



**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