

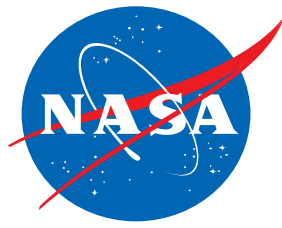
# Dynamic Radioisotope Power Systems

Conference on Advanced Power Systems for Deep Space  
Exploration

October 24, 2018

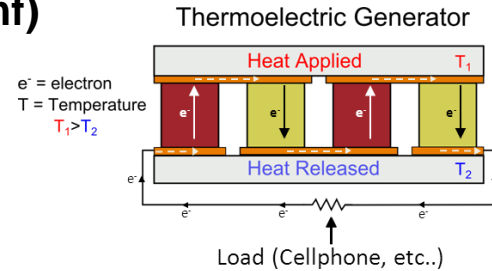
Salvatore Oriti  
NASA Glenn Research Center  
Thermal Energy Conversion Branch

# Energy Conversion Options for Radioisotope Power Systems



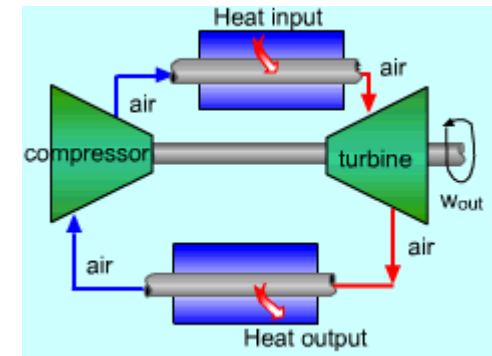
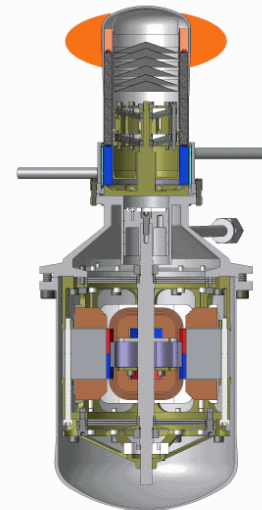
## Static

- Thermoelectrics (Seebeck effect, heat direct to emf)
- Solid-state, no moving parts
- Demonstrated reliability and long life (Voyager, Cassini, New Horizons, Mars Curiosity)
- Other options : Thermo-photovoltaic, thermionic

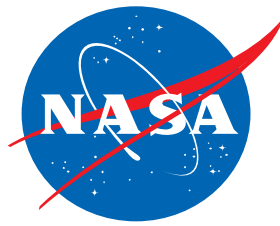


## Dynamic

- Heat engines (Stirling, Brayton, Rankine)
- Moving parts (Pistons, turbines, alternators)
- Heat to mechanical, to electrical energy
- Can be designed to eliminate wear mechanisms, and have infinite fatigue life
- Never flown in space as power convertor
- Multiple free-piston Stirling cryocoolers have operated long-term in space, up to 20 years



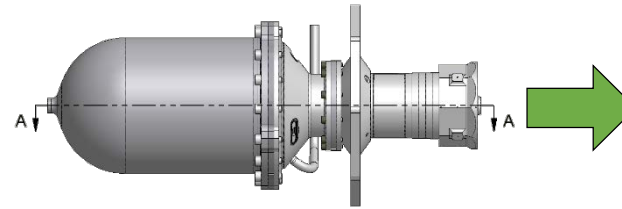
# Dynamic-Conversion Power System Background



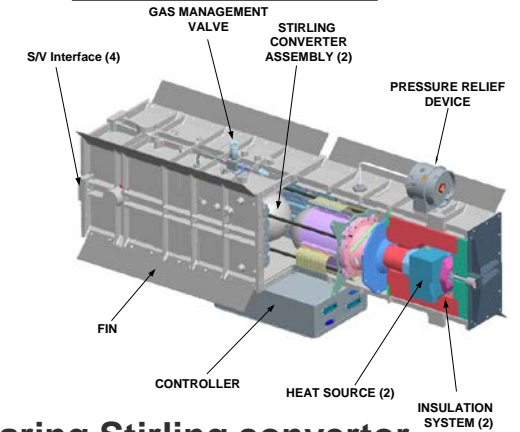
## SRG-110

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

## Convertor



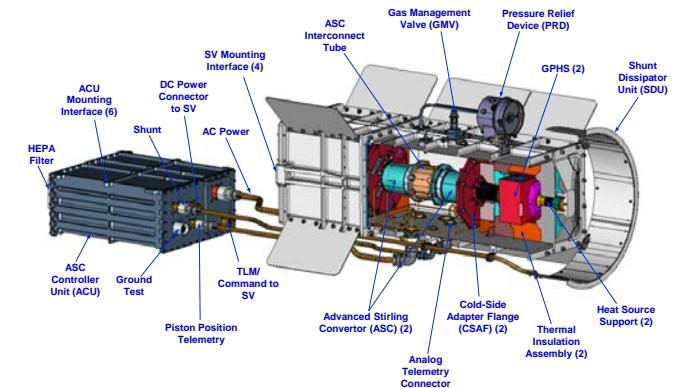
## Generator



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

## ASRG

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



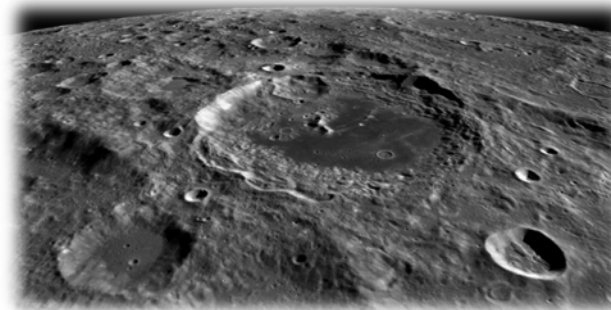
**ASRG, using gas-bearing Stirling convertor**  
(image credits : Sunpower, Lockheed Martin)

# Current Dynamic Converter Development



Item	Performance Goal
Life	20 years
Efficiency	$\geq 24\%$ at $T_{\text{cold}} > 100\text{ }^{\circ}\text{C}$
Specific Power	$\geq 20\text{ W}_e/\text{kg}$ (converter 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

Goals make converter designs applicable to a wide range of missions



Lunar  
(Far side & South Aitken Basin)



Europa

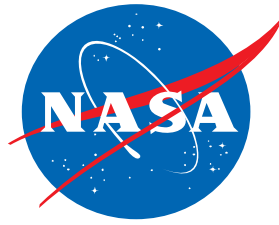


Titan

## Robustness goals also defined:

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

# Convertor Development Timeline



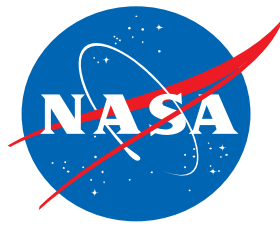
Status	Date	Description
✓	2016-Aug	RFP Release
✓	2016-Nov	Proposal review
✓	2017-Jul	Contract awards (4)
✓	2017-2018	Phase 1 - Design
✓	2018-Apr	Decision Gate 1
Ongoing	2018-2020	Phase 2 – Fab & Test
Future	2020-2021	Phase 3 – IV&V
Future	2021	Tentative Decision Gate 2
Future	2021	Goal : Begin DOE flight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

## Convertor development contracts awarded in 2017:

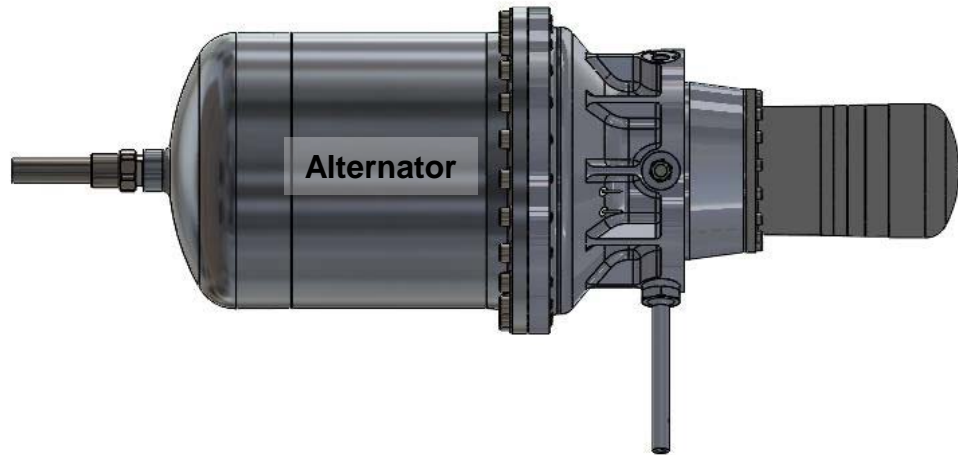
Item	Flexure Isotope Stirling Convertor (FISC) American Superconductor, Inc.	Turbo-Brayton Convertor (TBC) Create, LLC	Thermo-Acoustic Power Convertor (TAPC) Northrop Grumman	Sunpower Robust Stirling Convertor (SRSC) Sunpower, Inc.
Power ( $W_e$ )	70	355	110	65
Efficiency (%)	31	26	26	29
Hot-end Temp ( $^{\circ}C$ )	650	730	700	720
Mass (kg)	3.3	15.5	6.4	2.0
Specific Power ( $W_e/kg$ )	21	22	17	33
Phase 2 awarded	Yes	Yes	No	Yes

# Flexure Isotope Stirling Convertor (FISC)

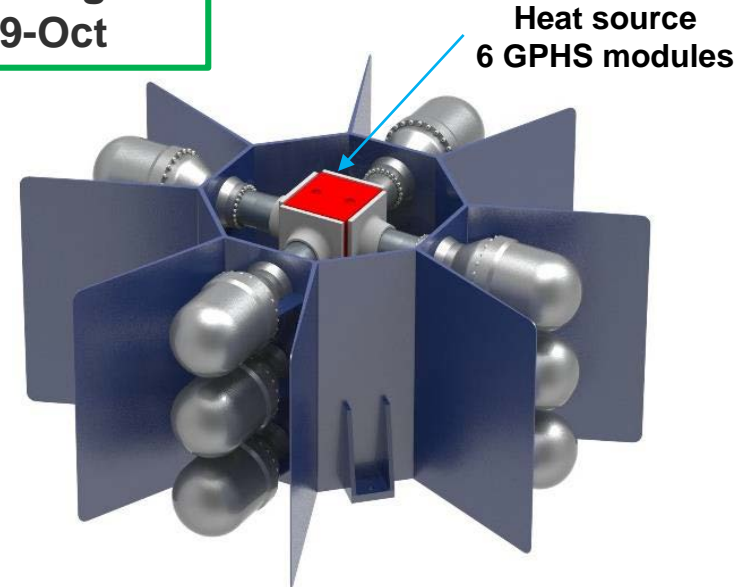
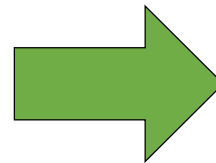
American SuperConductor (AMSC), formerly Infinia Tech Corp.



Phase 2 awarded : 2018-April  
 Component fabrication has begun  
 Prototype delivery : 2019-Oct



70 W Flexure Isotope Stirling Convertor (FISC)



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

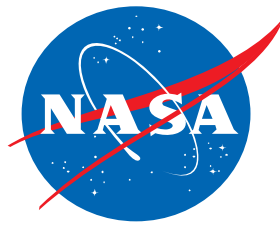
## FISC Characteristics

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)

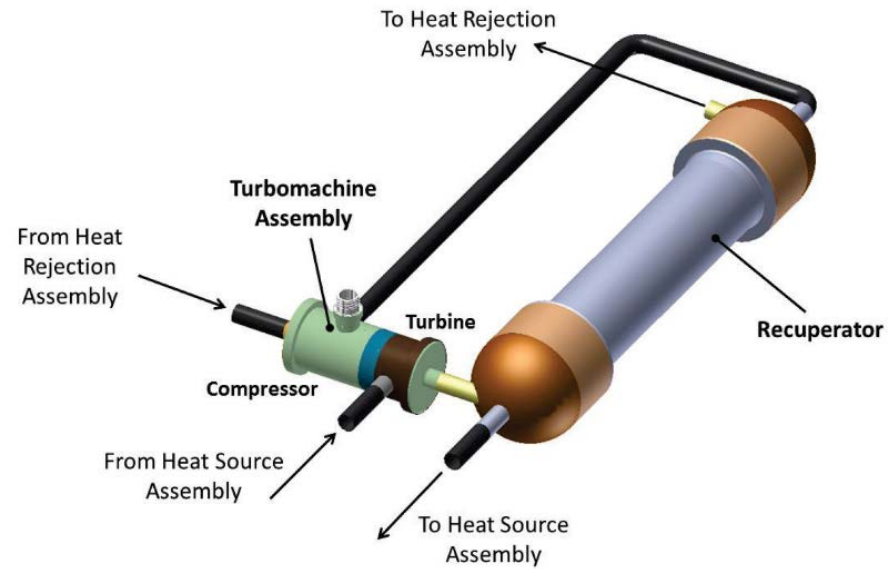
- Flexure-bearings, beta arrangement free-piston Stirling convertor
- Derivative of Technology Demonstration Convertor (TDC) from SRG-110 project
- TDCs have established long operational life via convertor testing at GRC
- Design deltas relative to TDC to improve the following:
  1. Higher radial stiffness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

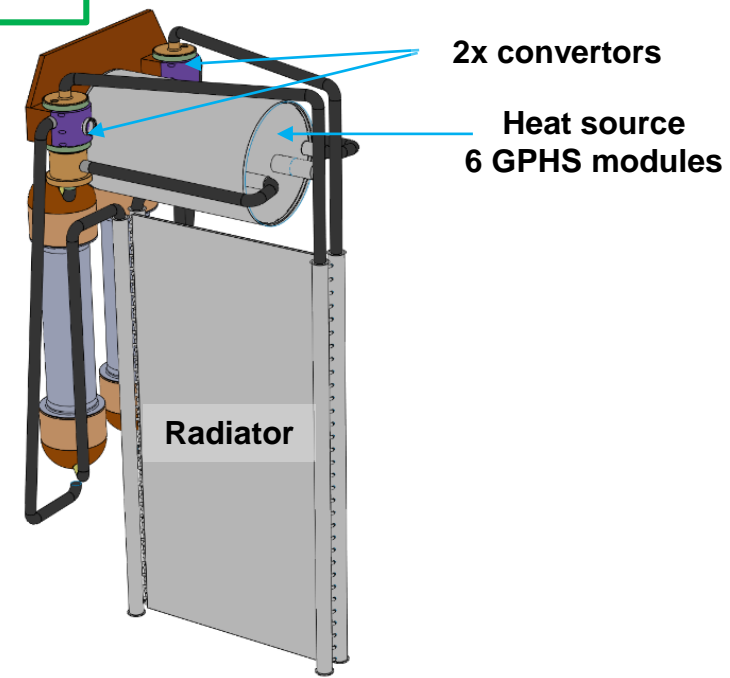
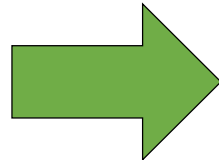
Creare, LLC



Phase 2 awarded : 2018-April  
 Component fabrication has begun  
 Prototype delivery : 2019-Oct



355  $W_e$  Turbo-Brayton Converter (TBC)



Notional 355  $W_e$  generator concept with 100% converter redundancy

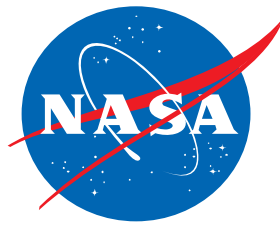
## TBC Characteristics

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 $W_e/kg$ )

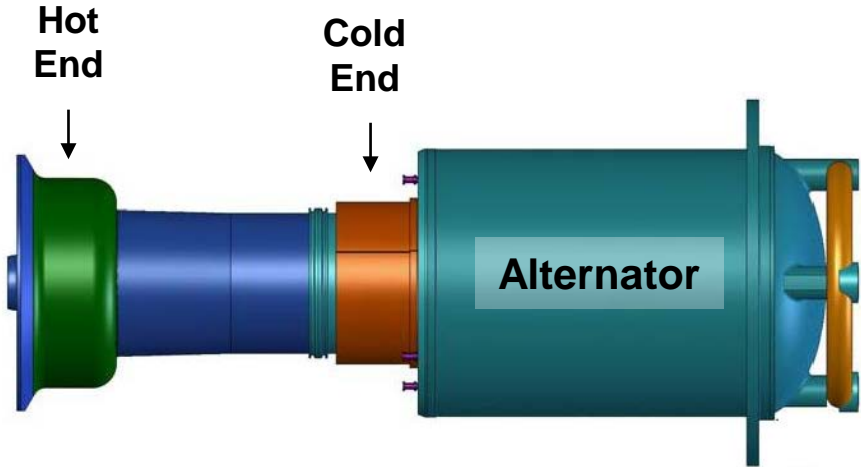
- Closed Brayton continuous flow cycle with recuperation
- Scaled-down from previous designs
- Life-limiting engineering : Hot-end material creep from centrifugal stress
- Recuperator is large portion of converter mass
- Two counter-rotating units permits redundancy, and nullifies angular momentum
-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

# Sunpower Robust Stirling Convertor (SRSC)

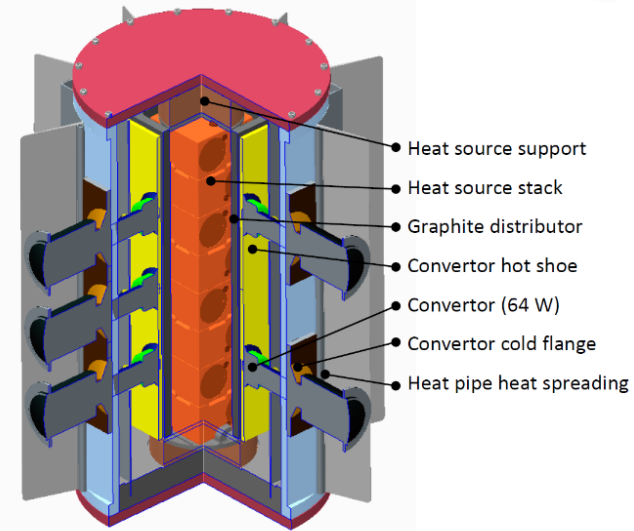
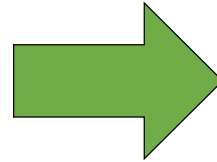
Sunpower, Inc.



Phase 1 : Complete  
Phase 2 awarded in process  
Prototype delivery : 2019-Jan



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



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

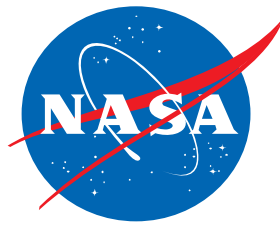
## SRSC Characteristics

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:

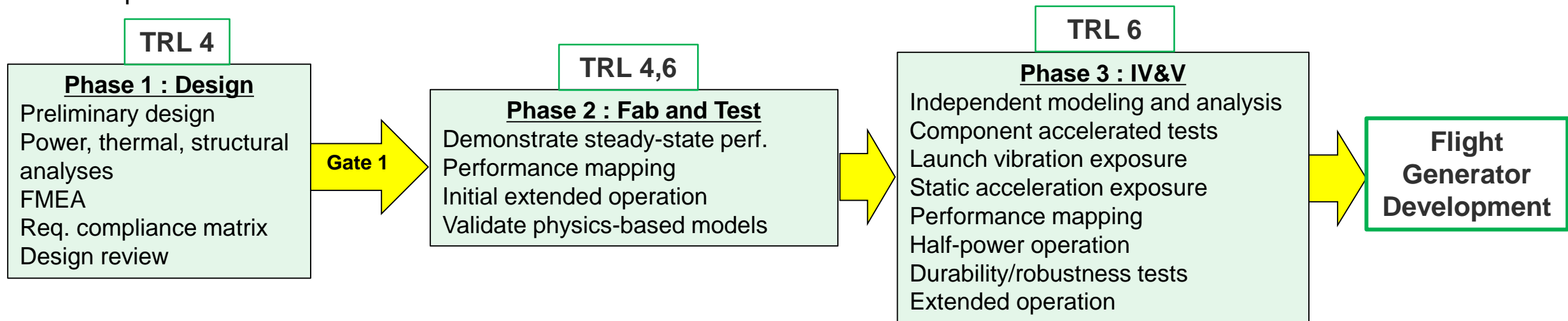
**Achieve convertor TRL 6, then initiate generator flight development**

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

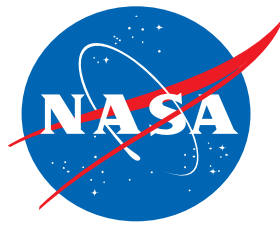
**Relevant environments can be simulated**

## 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



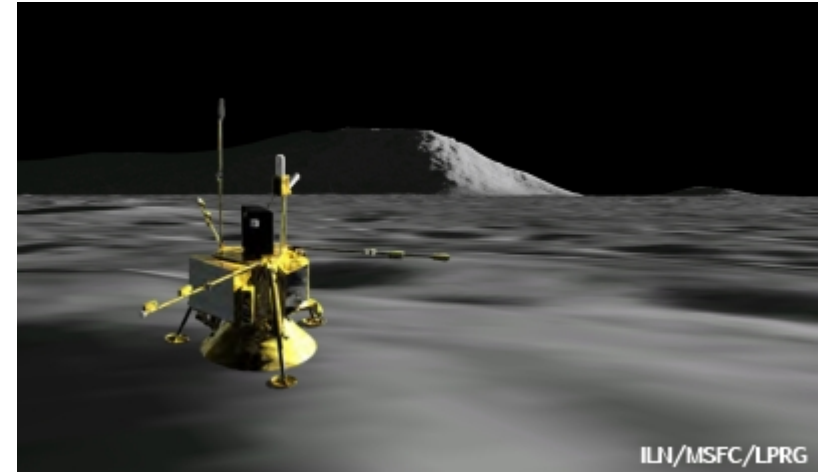
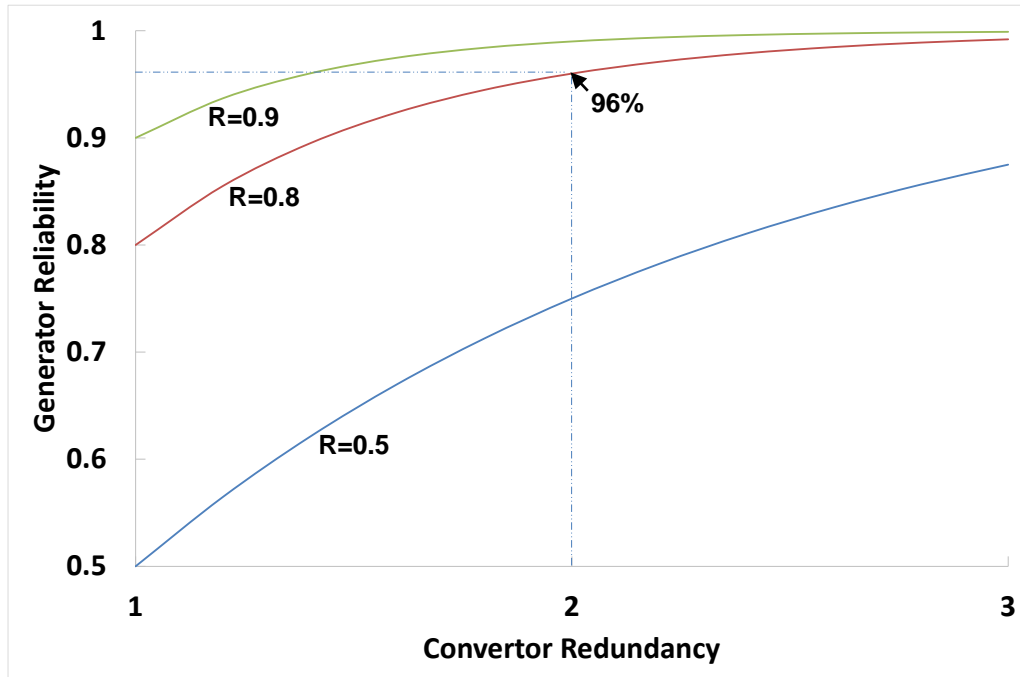
# First Mission Potential



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

## 20 year life requirement is atypical

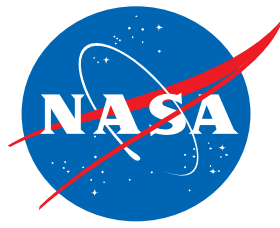
- Demonstrating 2x life via experiment is not realistic
- Statistical reliability analysis will have small number of hardware data points
- Fabrication of tens of hardware data points not possible on current timeline
- Converter-level accelerated testing not possible
- Converter component accelerated 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:
  - 330-hr darkness
  - Permanently-shadowed craters

# Generator and Converter Risk Mitigation



**Is dynamic conversion worth the risk?  
What can be done to encourage adoption?**

## **Dynamic Conversion Advantages:**

- Higher thermal-to-electric efficiency (up to 40%)
- Lower waste heat to output power ratio
- No degradation
- Low generator power decline (fuel decay only)
- Large multi-mission generator design space
- Extensible to high power levels

## **Converter risk mitigation:**

- Long-term material property data (metals and organics)
- Radiation endurance
- Component accelerated tests
- Robustness demonstrations (perhaps test to destruction)
- Develop enhancing products (e.g. debris-free regenerator)

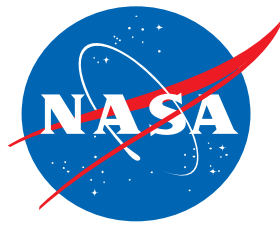
## **Ideal spacecraft power source (target these traits):**

- Reliable, always producing power
- Consistent output through every mission environment (behaves as a constant-voltage power source)
- High power density and specific power
- No disturbance to spacecraft (EMI, vibration, thermal)
- Simple con-ops (for fueling, launch, EDL, cruise)
- No human-in-the-loop needed at any mission stage
- No ground-command intervention needed
- Robust (capable of unexpected situations outside norm, capable of internal component failure)

## **Generator risk mitigation:**

- Demonstrate concept with converter redundancy
- Demonstrate radiant heat source coupling to converter
- Simple controller development, with fault tolerance
- Test multiple generators on spacecraft electrical bus

# 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 (Cumulative)	Status
SRG-110 Infinia, Corp.	TDC #13*	Flexure	12.8	On-going
	TDC #14		12.1	Shutdown for disassembly and inspection
	TDC #15		11.9	On-going
	TDC #16		11.9	On-going
	SES #2**		0.5	On-going
ASRG Sunpower, Inc.	ASC-0 #3**	Gas	8.6	On-going
	ASC-E3 #3		2.5	Shutdown for disassembly and inspection
	ASC-E3 #4**		3.5	On-going
	ASC-E3 #6**		2.8	On-going
	ASC-E3 #8		2.3	On-going
	ASC-E3 #9		1.9	On-going
	ASC-L**		4.4	On-going

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

\*Current record-holder for maintenance-free heat engine runtime

\*\*Have undergone launch-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 flexure bearings

### ASC-E3 #3 will also be inspected (after 2.5 yrs of operation)

- Suspect an assembly error causing fluctuations in performance

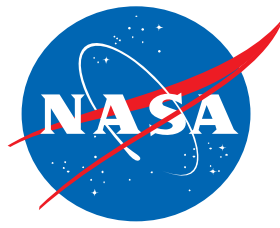


TDC #13  
extended operation setup



ASC-E3 pair  
extended operation setup

# Conclusions and Next Steps



**NASA's dynamic power convertor development for high-efficiency RPS is progressing as planned, and will result in advancements in power options for Exploration and Science missions**

- **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 IV&V and risk mitigation plans
  2. Execute these plans
  3. Finalize generator flight development path