Dynamic Radioisotope Power Systems

Conference on Advanced Power Systems for Deep Space Exploration

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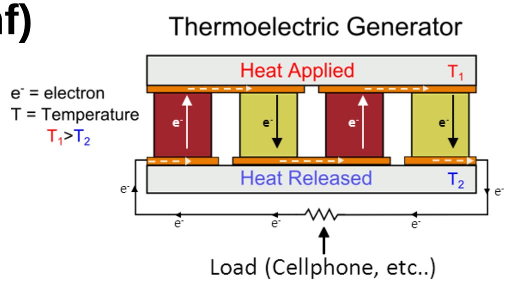
Energy Conversion Options for Radioisotope Power Systems

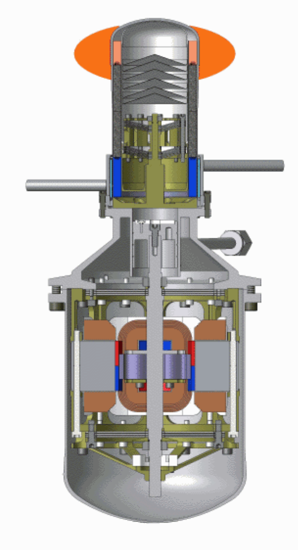
Static

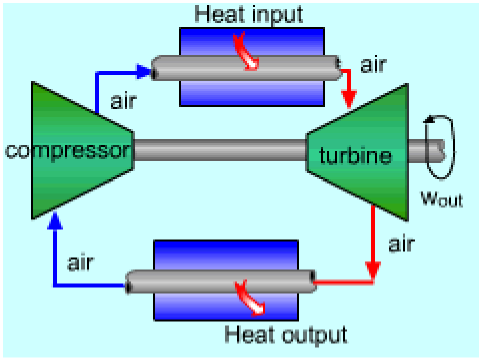
- Thermoelectrics (Seebeck effect, heat direct to emf)
- Solid-state, no moving parts
- Demonstrated reliability and long life (Voyager, Cassini, New Horizons, Mars Curiosity)
- Other options : Thermo-photovoltaic, thermionic



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

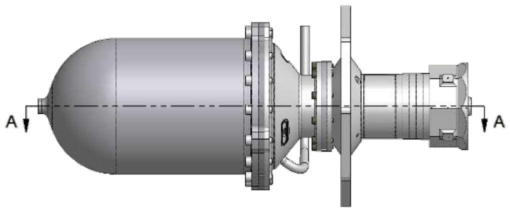
SRG-110

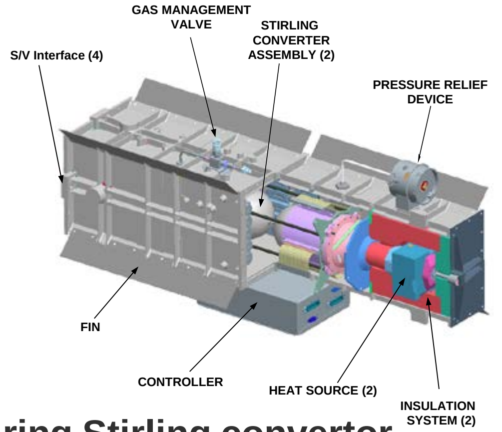
- ~114 W_e output
- Infinia's Technology Demonstration Convertor (TDC)
- 2 Pu-238 GPHS modules
- Overall efficiency = 23%
- 4.2 W_e/kg (before engineering unit build)
- Developed during 2001 to 2006 timeframe

ASRG

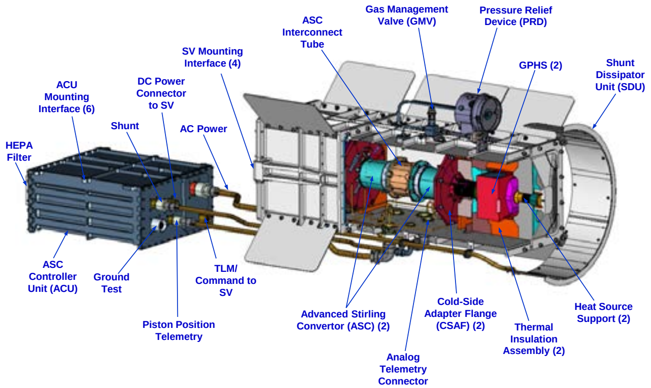
- ~140 W_e output
- Sunpower's Advanced Stirling Convertor (ASC)
- 2 GPHS modules
- Overall efficiency = 28%
- 4.4 W_e/kg
- Developed during 2006 to 2013 timeframe

Convertor **Generator**





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

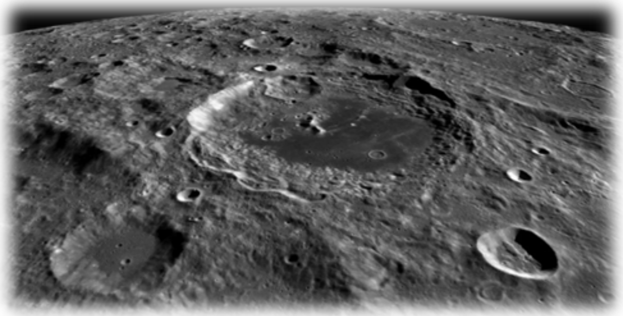


ASRG, using gas-bearing Stirling convertor
(image credits : Sunpower, Lockheed Martin)

Current Dynamic Convertor Development

Item	Performance Goal
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

Goals make convertor 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

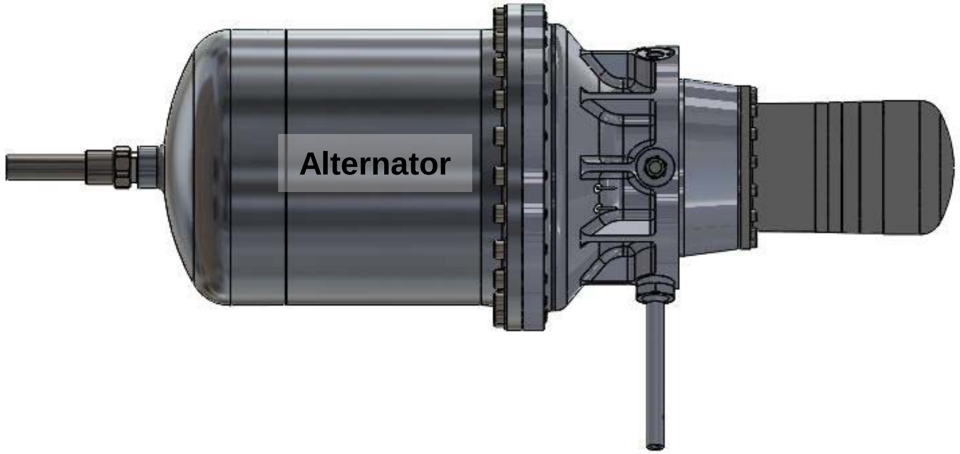
Convertor development contracts awarded in 2017:

Item	Flexure Isotope Stirling Convertor (FISC) American Superconductor, Inc.	Turbo-Brayton Convertor (TBC) 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
Phase 2 awarded	Yes	Yes	No	Yes

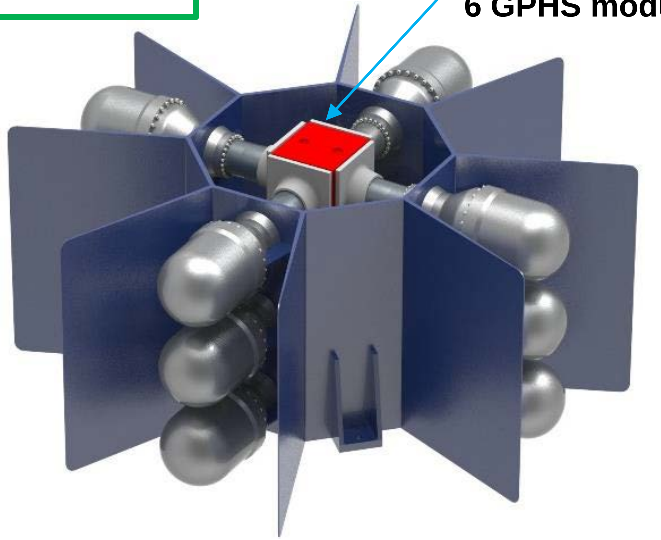
Flexure Isotope Stirling Convertor (FISC)

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_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)

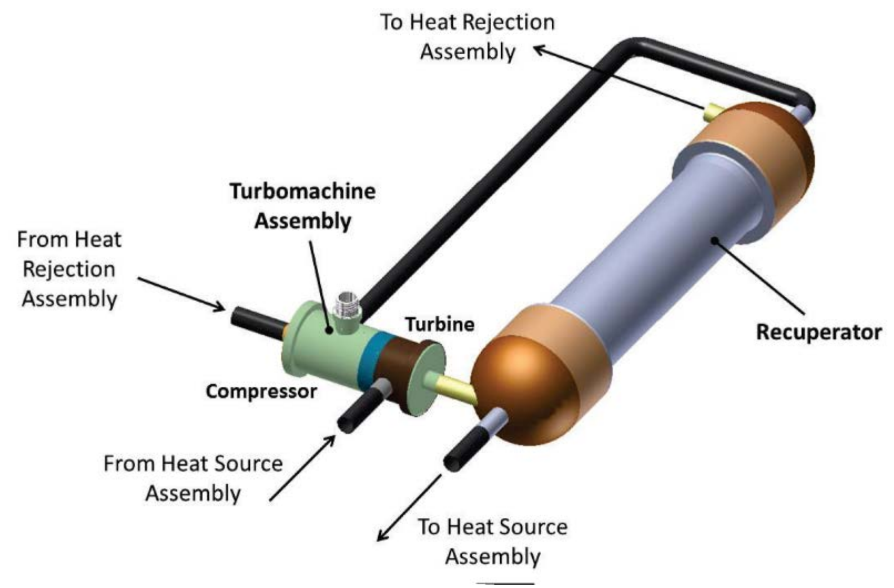
- **Flexure-bearings, beta arrangement free-piston Stirling convertor**
- **Derivative of Technology Demonstration Convertor (TDC) from SRG-110 project**
- **TDCs have established long operational life via convertor testing at GRC**
- **Design deltas relative to TDC to improve the following:**

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

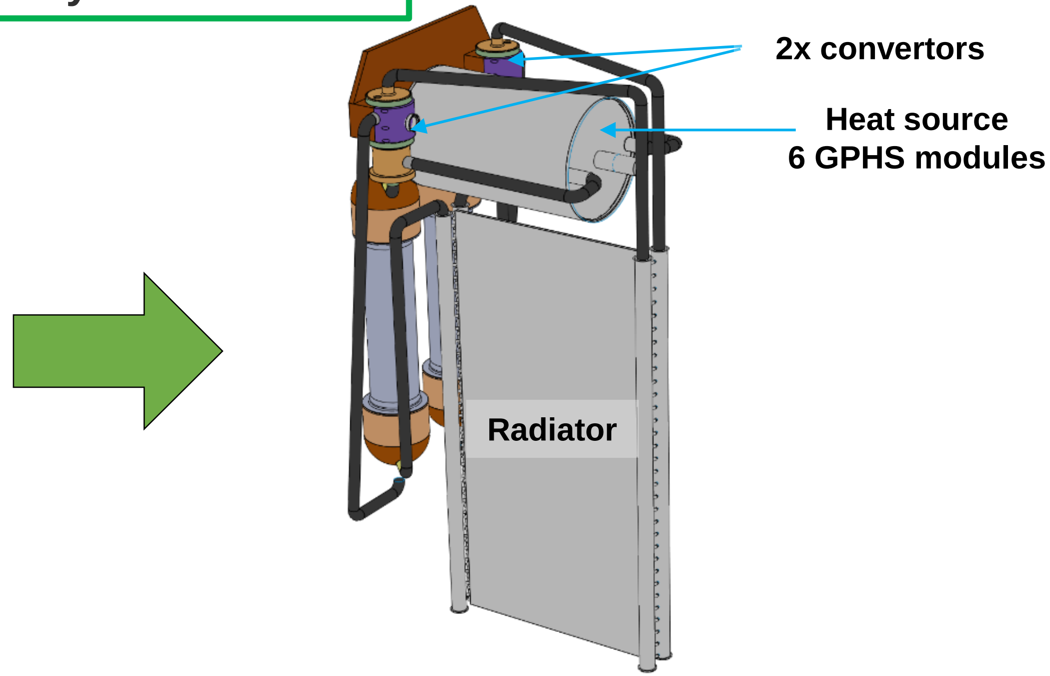
Turbo-Brayton Convertor (TBC)

Creare, LLC

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



355 W_e Turbo-Brayton Convertor (TBC)



Notional 355 W_e generator concept with 100% convertor redundancy

TBC Characteristics

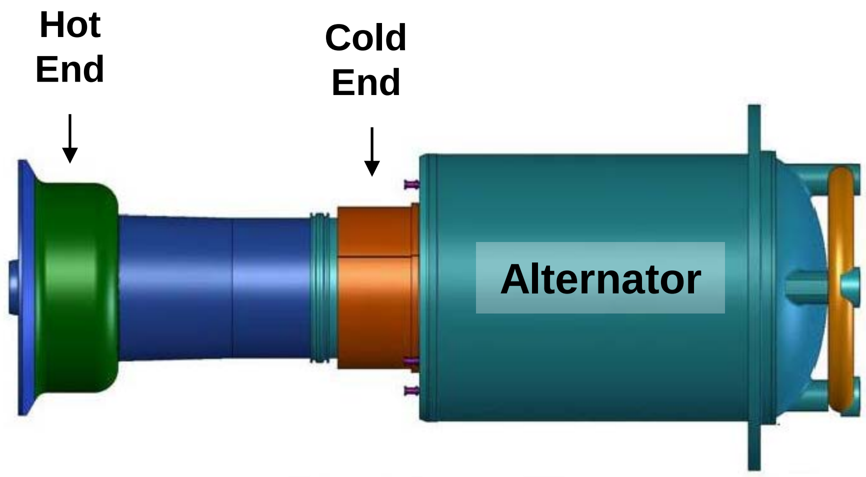
Power Output	355 W_e
Efficiency	26% @ T_{COLD}=100°C
Fraction of Carnot	0.41
Turbine Inlet Temp	730 °C
Mass	15.5 kg (22 W_e/kg)

- **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**

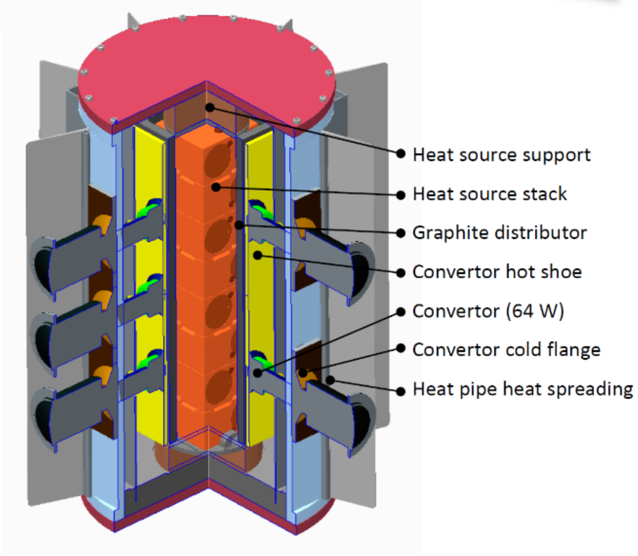
Sunpower Robust Stirling Convertor (SRSC)

Sunpower, Inc.

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



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

TRL 4

Phase 1 : Design
Preliminary design
Power, thermal, structural analyses
FMEA
Req. compliance matrix
Design review

Gate 1 →

TRL 4,6

Phase 2 : Fab and Test
Demonstrate steady-state perf.
Performance mapping
Initial extended operation
Validate physics-based models

→

TRL 6

Phase 3 : IV&V
Independent modeling and analysis
Component accelerated tests
Launch vibration exposure
Static acceleration exposure
Performance mapping
Half-power operation
Durability/robustness tests
Extended operation

→

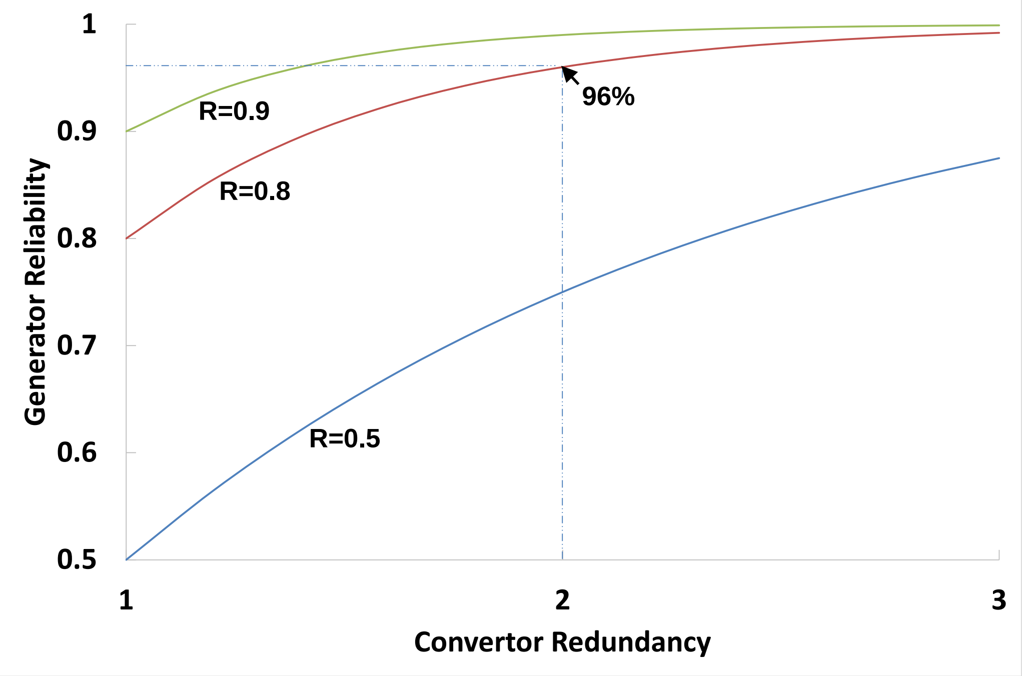
Flight Generator Development

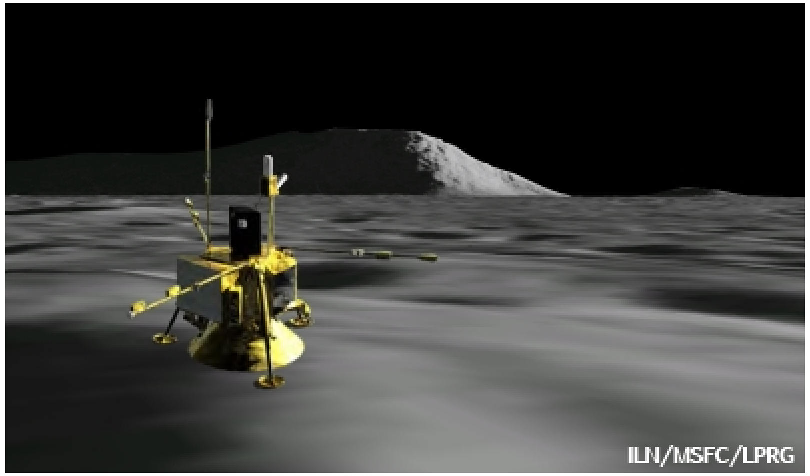
First Mission Potential

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:
  - 330-hr darkness
  - Permanently-shadowed craters

Generator and Convertor 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

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)

Convertor 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)

Generator risk mitigation:

- Demonstrate concept with convertor redundancy
- Demonstrate radiant heat source coupling to convertor
- 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