National Aeronautics and Space Administration

Dynamic RPS Path to Flight

Nuclear and Emerging Technologies for Space

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Thermal Energy Conversion Branch

Dynamic Energy Conversion

Strong case for use in RPS-powered science missions

- Wear mechanisms can be eliminated
- Higher thermal-to-electric efficiency (up to 40%)
- Lower waste heat to output power ratio
- No conversion device degradation
- Low generator power decline (due to fuel decay only)
- Same convertor usable by different mission types
- Extensible to high power levels

Design life supported by flight-relevant convertor operation:

Project & Provider	Test Article	Years of Operation (Cumulative)	Status	Bearing Technology
SRG-110 Infinia, Corp.	TDC #13*	13.2	On-going	Flexure
	TDC #14	12.0	Shutdown for inspection	
	TDC #15	12.3	On-going	
	TDC #16	12.3	On-going	
	SES #2**	1.0	On-going	
ASRG Sunpower, Inc.	ASC-0 #3**	9.0	On-going	Gas
	ASC-E3 #4**	3.9	On-going	
	ASC-E3 #6**	3.0	On-going	
	ASC-E3 #8	2.6	On-going	
	ASC-E3 #9	2.3	On-going	
	ASC-L**	4.8	On-going	

Cumulative Per-Convertor Runtime as of February 2019

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

******Have undergone launch-vibe portion of life certification

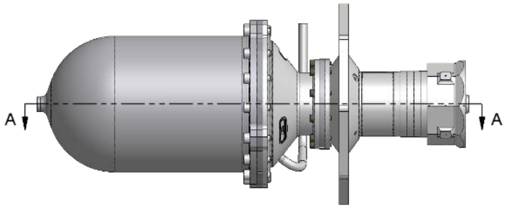
DRPS Historical System Development

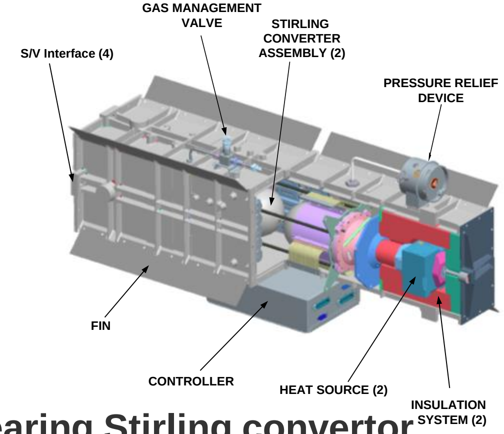
Convertor

Generator

SRG-110 (2001 to 2006)

- Engineering unit assembly initiated
- ~114 W_e output
- Infinia's Technology Demonstration Convertor (TDC)
- 2 Pu-238 GPHS modules
- Overall efficiency = 23%
- Developed during 2001 to 2006 timeframe

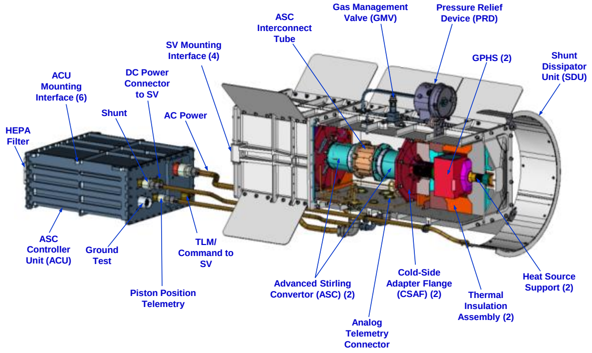




SRG110, using flexure-bearing Stirling convertor
(image credit : Lockheed Martin)

ASRG (2006 to 2013)

- Qual unit assembly initiated
- ~140 W_e output
- Sunpower's Advanced Stirling Convertor (ASC)
- 2 GPHS modules
- Overall efficiency = 28%
- ~4 W_e/kg
- Developed during 2006 to 2013 timeframe

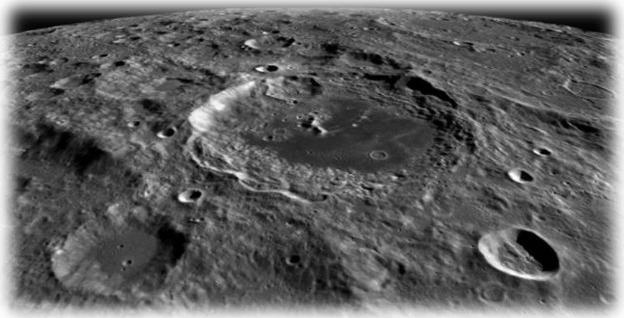


ASRG, using gas-bearing Stirling convertor
(image credits : Sunpower, Lockheed Martin)

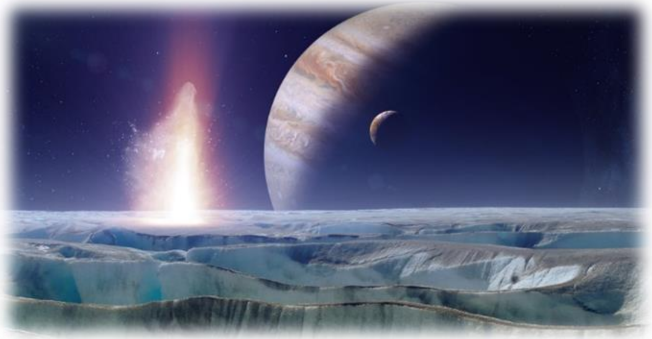
DRPS Requirements (Draft)

- **Goals make generator designs applicable to a wide range of missions**
- **Derived from Surrogate Mission Team input**

Item	Requirement
Life	17 years (3 storage + 14 mission)
Efficiency	≥ 20 %
Specific Power	≥ 2 W_e/kg
Fault tolerance	Capable of at least 1 convertor failure
Degradation	< 1.3 % per year
Mission Environments	Deeps space, Lunar, Titan, Europa, Enceladus
Structural Dynamics Environments	Launch vibe 20g static acceleration
Radiation	300 krad
Size	Fits in DOE shipping container



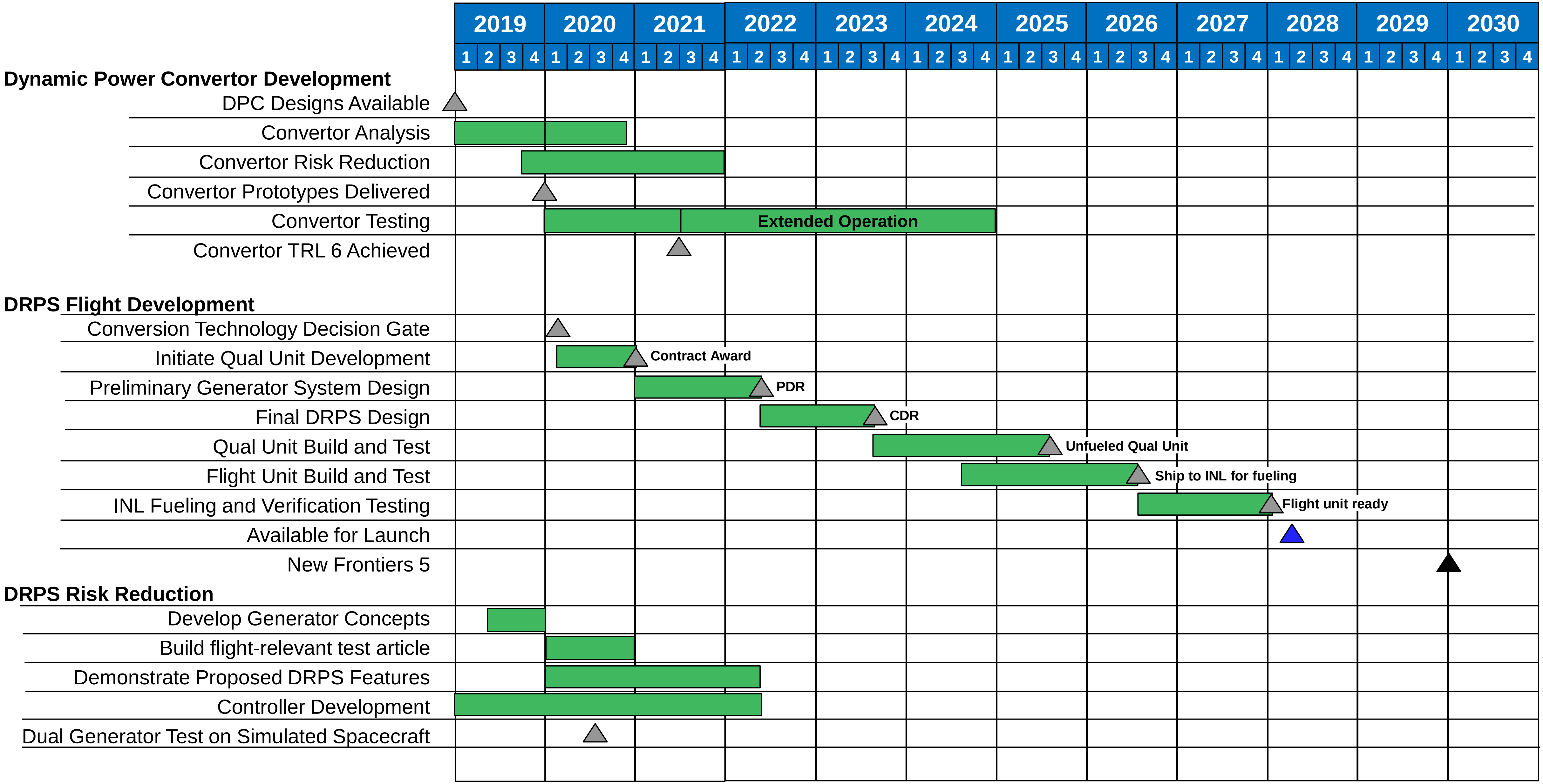
Lunar
(Far side & South Aitken Basin)



Europa

Titan

DRPS Notional Schedule

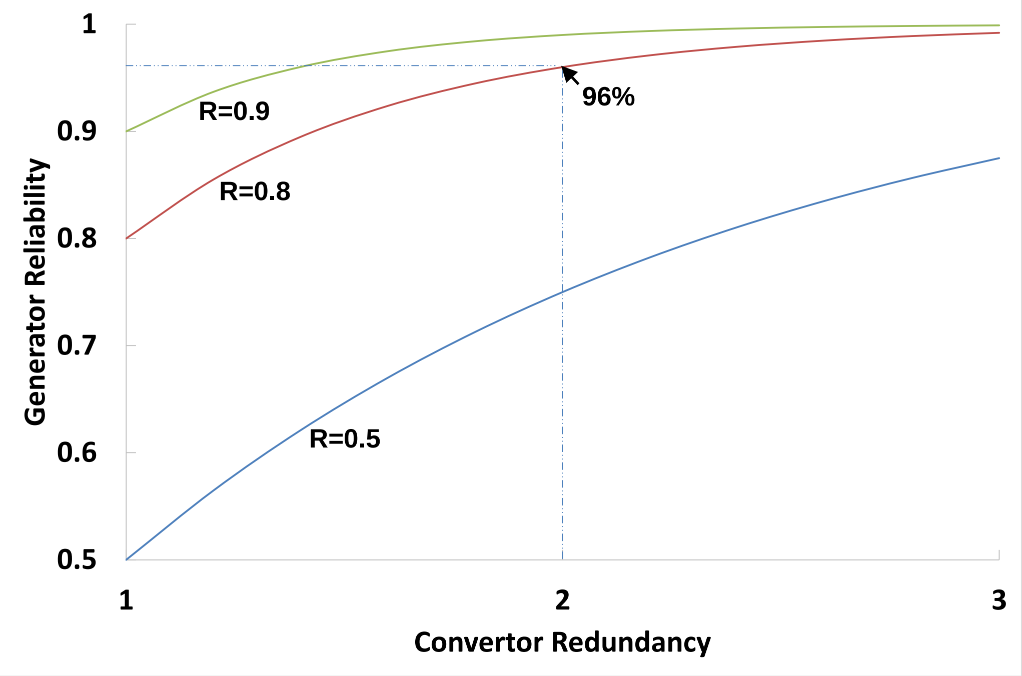


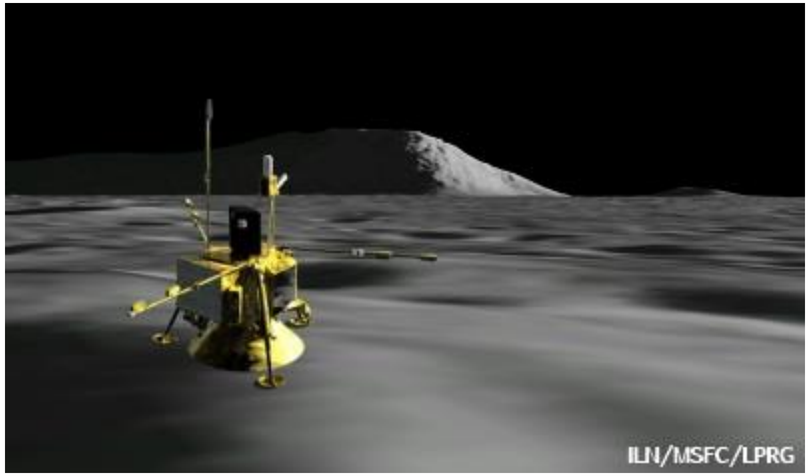
First Mission Potential

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





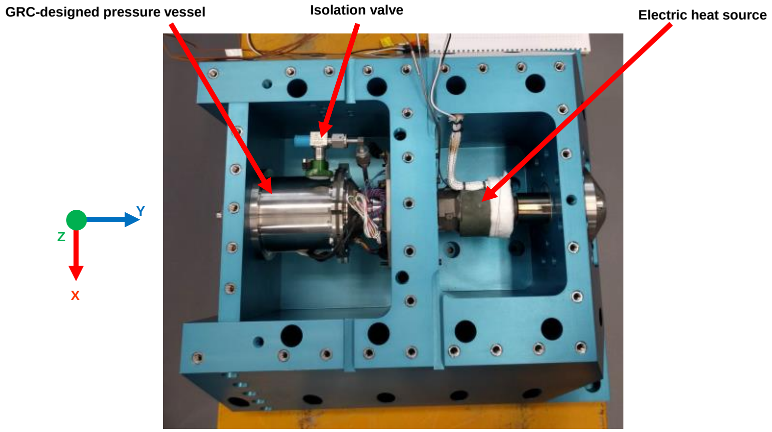
Lunar mission is an attractive first use

- 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?

Ideal spacecraft power source (target these traits):
- Reliable, always producing power
- Consistent output during every mission environment
- 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: Margin, fault tolerance, redundancy

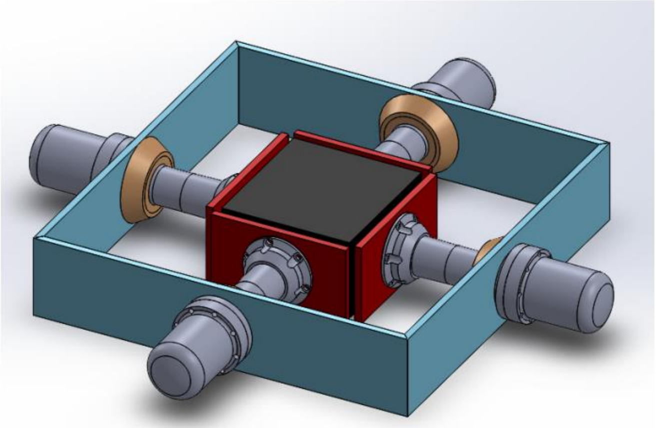


Vibration simulation test

GRC-developed analog controller

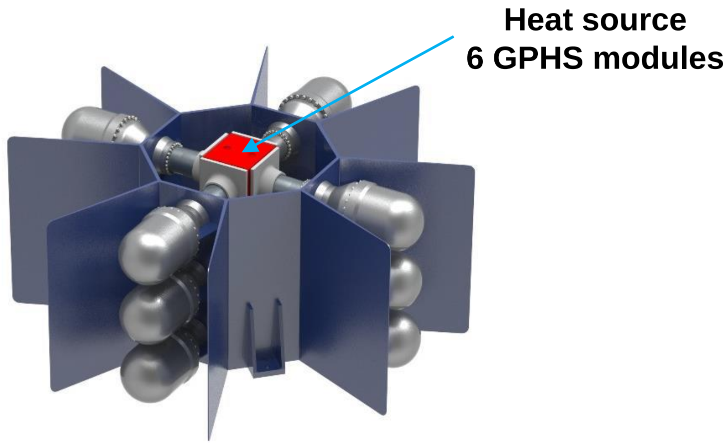
Convertor risk mitigation:
- Long-term material property data (metals and organics)
- Radiation endurance
- Component accelerated tests
- Robustness demonstrations (perhaps test to destruction)
- Develop enhancing products (e.g. debris-free regenerator)

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

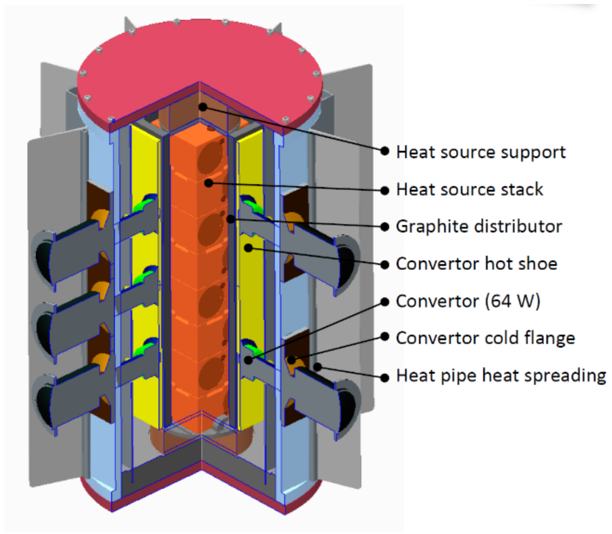


GRC-developed generator concept

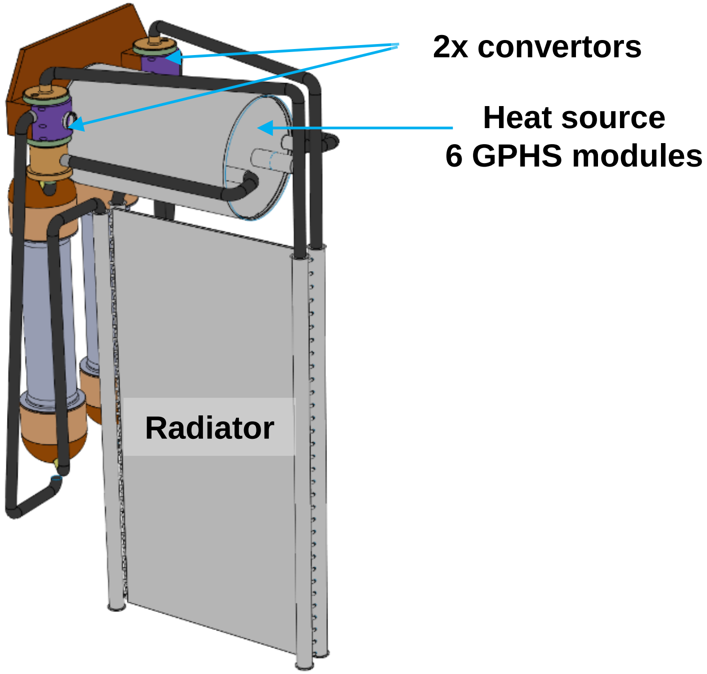
Example System Concepts



Notional 420 W_e generator concept with 100% convertor redundancy
(AMSC's Flexure Isotope Stirling Convertors)



Notional 500 W_e generator concept with 25% convertor redundancy
(Sunpower's Robust Stirling Convertor)

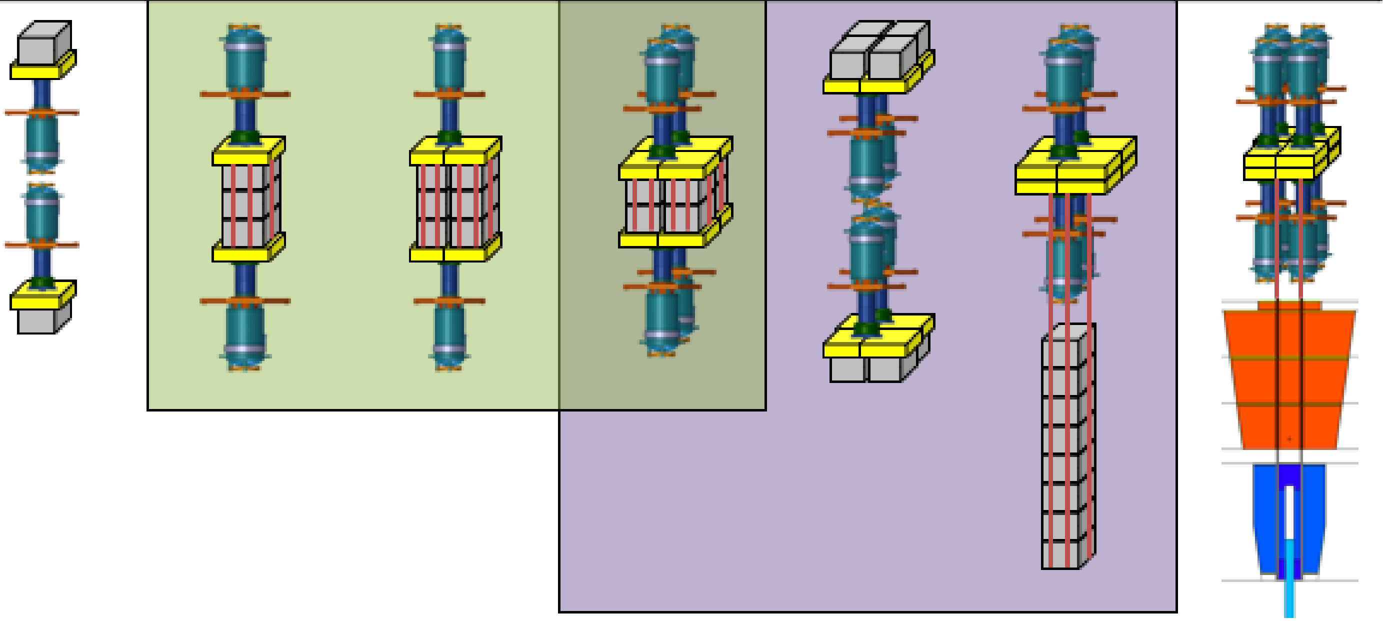


Notional 355 W_e generator concept with 100% convertor redundancy
(Creare's Turbo-Brayton Convertor)

GRC's System Concept Evaluation

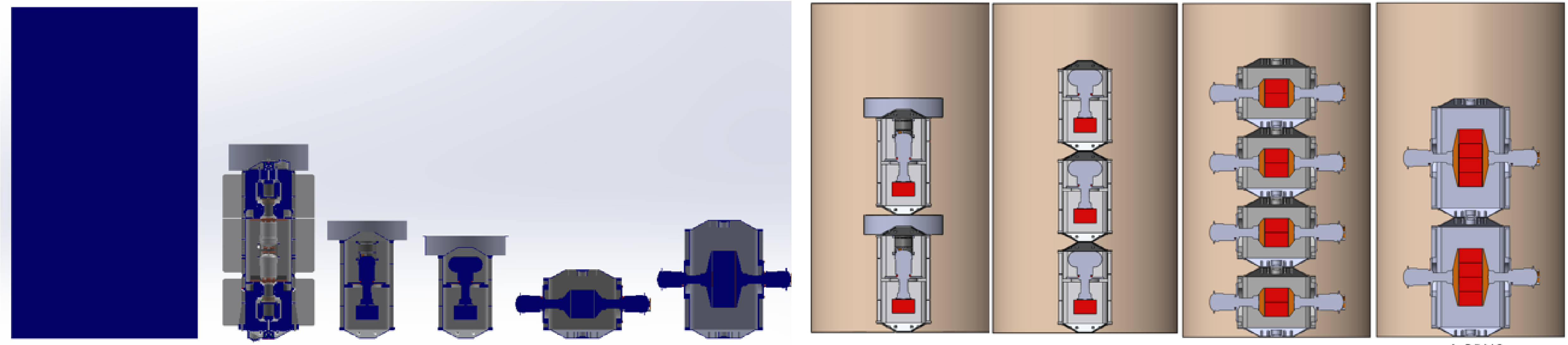
- **Centrally located heat source allows heat sharing, convertor redundancy**
- **Heat source can be remotely located, AND shared amongst convertors (requires heat transport via heat pipes)**

<table>
<tr><th></th><th>ASRG</th><th>SRG-200</th><th>SRG-400</th><th colspan="3">SRG-500</th><th>KP-1</th></tr>
<tr><td>BOM Power</td><td>140 We</td><td>193 We</td><td>370 We</td><td colspan="3">495 We</td><td>1097 We</td></tr>
<tr><td>No. GPHS</td><td>2</td><td>3</td><td>6</td><td colspan="3">8</td><td>Fission</td></tr>
<tr><td>Heat Source Config.</td><td>Distributed & dedicated</td><td colspan="3">Centralized & shared using heat pipes</td><td>Distributed & dedicated</td><td colspan="2">Distributed & shared using heat pipes</td></tr>
<tr><td>Stirling Config.</td><td>2X 80W ASC</td><td colspan="2">2X 200W ASC-H</td><td colspan="3">4X 200W ASC-H</td><td>8X 200W ASC-H</td></tr>
</table>



GRC's System Concept Evaluation

- The envelope dimensions of any generator building block can be estimated
- Heat-engine length determined by operating frequency, but diameter grows with power
- Housing size set by required insulation thickness around GPHS module
- Central heat source arrangements have higher specific power
  - Lower GPHS thermal loss, closer coupling of rejection zone to radiator



Conclusions and Next Steps

A strategy has been formulated supporting flight of a dynamic-conversion RPS near 2028

- **Requirements are nearing completion**
- **Lessons learned from previous efforts are being implemented**
- **Design elements that enhance reliability and robustness are being considered**
- **Usability and ease of mission integration hold higher priority than performance**
- **Next steps:**

1. More detailed system concept generation
2. Initiate system concept hardware testing
3. Initiate system component risk reduction tasks
4. Pass conversion technology Gate Review ~ Feb 2020