National Aeronautics and Space Administration

NASA

1961

1971

1981

1991

2001

2011

2021

RADIOISOTOPE

POWER SYSTEMS PROGRAM

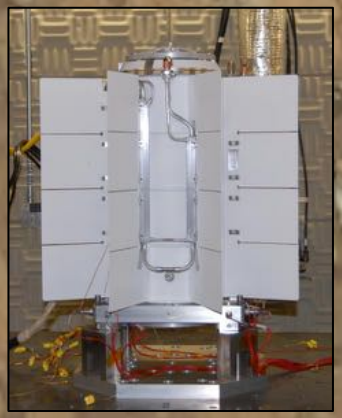
PRESENTATION TO THE OPAG
PRODUCTION OPERATIONS AND RPS SYSTEMS STATUS

June F. Zakrajsek, NASA
Tracey Bishop, DOE

September 7, 2017

1961

110 W_e BOM; 92.4 W_e currently (2011 -)



2021

Agenda

- Production Operations
  - Constant Rate Production
  - RPS Heat Source Production
- Systems
  - MMRTG
  - eMMRTG
  - Dynamic
  - Next Generation
- Summary

PRODUCTION OPERATIONS

NASA-DOE Structure

- On October 31, 2016, NASA and DOE renewed the Memorandum of Understanding
  - Documents agency roles and responsibilities
  - Emphasizes integration to ensure mission success
- DOE Office of Nuclear Energy serves as primary interface for **nuclear** missions
  - Agency interface elevated to Deputy Assistant Secretarial level to strengthen coordination and visibility to identify synergies

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DOE Production Operations

Production Operations consist of two main areas:

- Operations and Analysis (O&A) covers activities to support the manufacturing and delivery of RPS systems
  - Infrastructure Costs
  - Equipment Maintenance & Refurbishment
  - Qualified Operators and Processes
- Plutonium Supply Project covers activities to re-establish and produce plutonium-238 to fuel RPS systems

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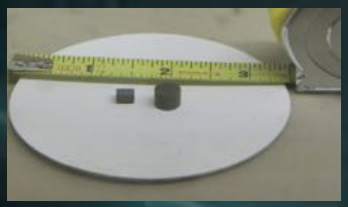
DOE RPS Supply Chain

Pu-238 Isotope Production
- Oak Ridge National Laboratory
- Idaho National Laboratory



Fueled Clad Manufacturing
- Oak Ridge National Laboratory
- Los Alamos National Laboratory

Fueling/Testing/Delivery
- Idaho National Laboratory

Launch Support
- Idaho National Laboratory

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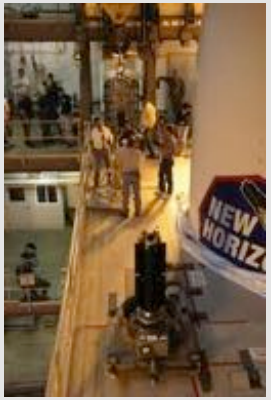
DOE Mission Support

RTG Assembly

Shipping and
Kennedy Space Center
Ground Operations

GPHS Heat Source Assembly

Acceptance Testing:
vibrational, mass property,
magnetics and thermal
vacuum



Launch Site
Support

Mission Safety Analysis
for Launch Approval

DOE Constant Rate Production

- Transition to Constant Rate Production
  - Established annual average production rates for Pu-238 and fuel clads, across the DOE RPS supply chain
  - Transitioning Pu-238 Supply from a project-based approach to a campaign model
  - Accelerating research to optimize the supply chain
  - Improving integration of RPS activities across the DOE complex to inform future investment decisions

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Constant Rate Production (CRP) & Pu238 Production

- CRP leverages DOE standard campaign model providing flexibility for NASA missions
  - Reduces mission risk by maintaining qualified work force and making targeted equipment investments across the supply chain
  - Reduces mission costs by approximately 25%
- By fiscal year 2019
  - Maintain average production rate of 400 g/y
- By fiscal year 2021
  - Add additional irradiation capability at the Advanced Test Reactor (ATR) for redundancy
  - Maintain 10-15/year constant-rate of fueled clads
- By fiscal year 2025
  - Maintain average production rate of 1.5 kg/y with surge capacity to ~2.5 kg/y (as funded)
  - Completed modernization campaign at Los Alamos to improve reliability of critical infrastructure and enhance worker safety

Newly produce HS-PuO_2

Aqueous Processing Line at Los Alamos

10-15 fueled clads/year

(4 needed for a GPHS)

Constant Rate Production Benefits

- Leverages DOE standard campaign model providing flexibility for NASA missions
  - New irradiation target designs
  - Equipment investments for fuel clad manufacturing
  - Utilization studies for the Advanced Test Reactor
  - Evaluation of new technology
- Maintains qualified work force
- Reduces mission costs
  - New Frontiers initial estimates reduced approximately 25%
- Provides more predictable operation pace that level-loads resources

Constant Rate Production
Provides flexibility to allow for surge capabilities
Alleviates process and production limitations

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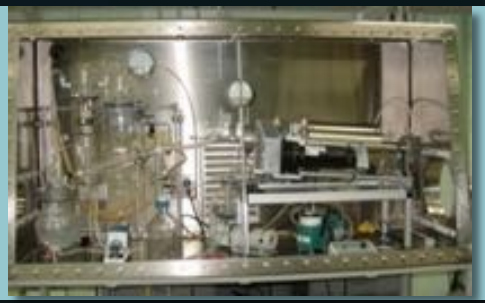
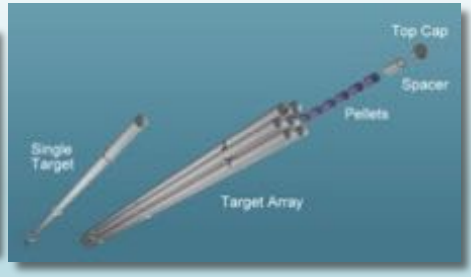
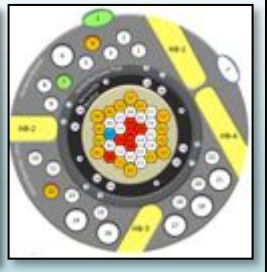
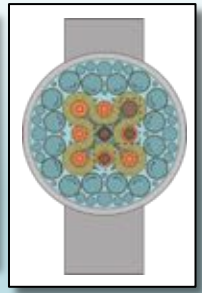
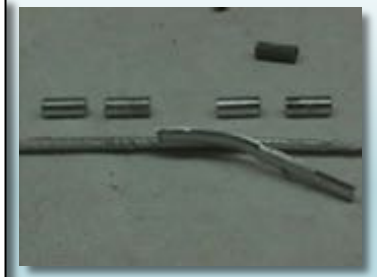
Stages of Pu238 Production Development

Neptunium Conversion to Oxide

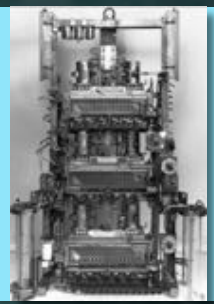
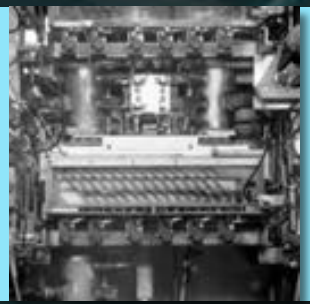


Target Fabrication, Irradiation, and Post-Irradiation Examination



Chemical Separations

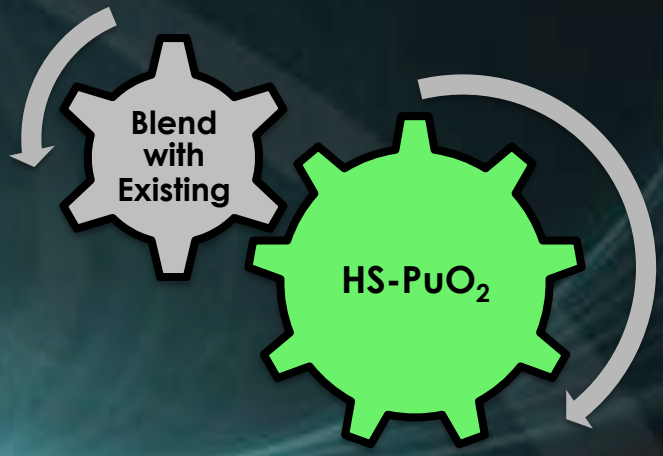
Pu238 Production Development

Objective: Restart domestic production of Heat Source Pu238 (HS-PuO_2)with a planned rate of 400 g/yr at the end of FY19 and 1.5 kg/yr at the end of FY25

- **First new US Pu-238 production since the late 1980s**
  - ~ 100 gm total HS-PuO_2 has been produced
  - End-to-End demonstration of production
    - Some new material has been used for Mars 2020 fueled clads (FC)
- Target production already well underway for second demonstration
  - Demonstrating larger batch sizes
  - Implementing process improvements
- Target Irradiation in the High Flux Isotope Reactor (HFIR) at ORNL continues
- Currently investigating options for additional target irradiation at the Advanced Test Reactor (ATR) at INL

Mars 2020 FC

New Production (1.5 kg/yr)



Results in potential 2-3 x HS-PuO_2 (3+ kg/yr)

SYSTEMS

Possible Future RPS

- enhanced Multi-Mission Radioisotope Thermoelectric Generator (e-MMRTG)
  - Retrofit the MMRTG with higher efficient thermoelectric (TE) couples
  - Midway through Technology Maturation Phase
- Next Generation RTG (Next Gen)
  - In-house TE maturation efforts
  - RFI followed by RFP for system concept and technology maturation long-pole plan
  - Initial planning phase
- Dynamic RPS (DRPS)
  - SOA assessment - complete
  - Requirements definition - complete
  - Multiple industry, multiple conversion technology contracts – imminent

Parameter	MMRTG	eMMRTG	Next Gen	DRPS
TRL	9	3	1-3	3-4
Potential Flight Readiness Target Date	2009	2022	2028	2026
P_0 - BOL (We)	110	148	400-500	200-500
Efficiency - $P_0/Q*100$ (%)	5.50%	7.40%	10-14%	20-25%
Specific Power - P_0/m (We/Kg)	2.4	3.3	6-8	4-6
Q - BOL (Wth)	2000	2000	4000	1000-2000
Average annual power degradation, r (%/yr)	4.8%	2.5%	1.9%	1.3%
P_{BOM} - $P=P_0*e^{-rt}$ (We)	110	137	375-470	195-485
Fueled storage life, t (years)	3			
P_{EODL} - $P=P_0*e^{-rt}$ (We)	49	80	290-360	170-420
Flight Design Life, t (yrs)	14			
Design Life, t (yrs)	17			
Allowable Flight Voltage Envelope (V)	22-36	22-34		
Planetary Atmospheres (Y/N)	Y	Y	N	Y

eMMRTG: What is being enhanced?

1961

1971

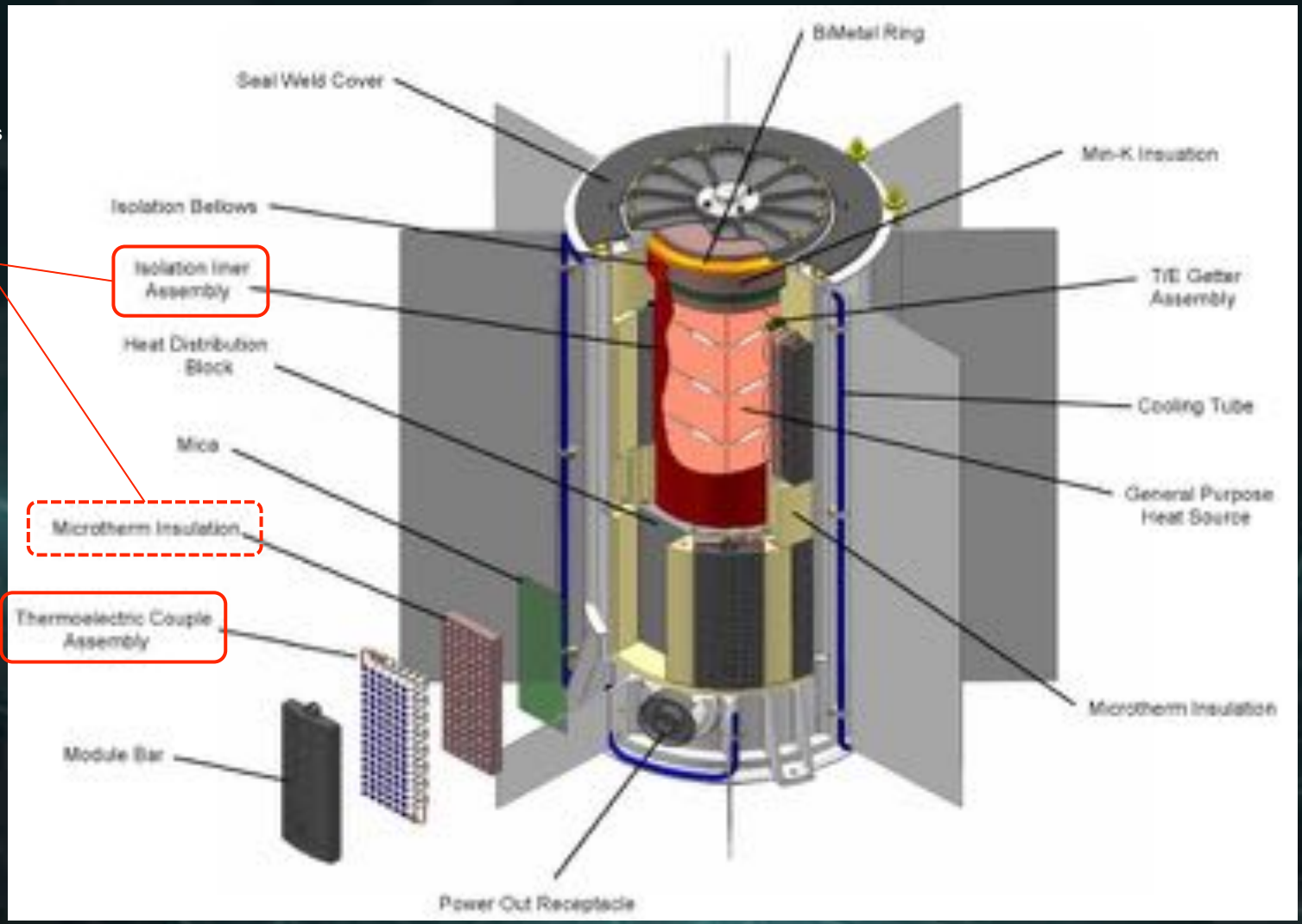
Enhancements under consideration

Known enhancements

Engineering:
- emissivity change to liner,
- substitute insulation

Changes needed to MMRTG

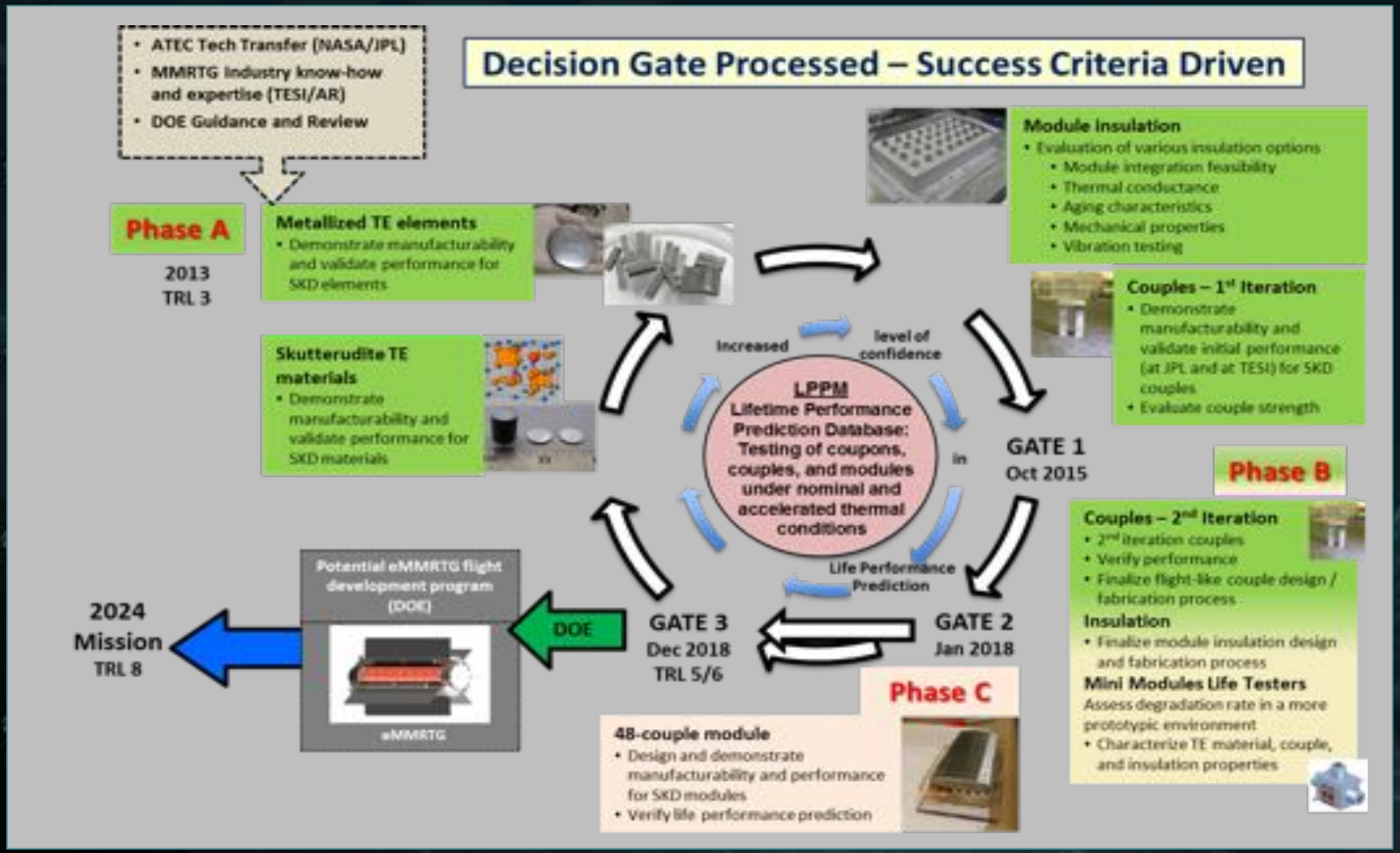
New Technology: Substitute SKD thermoelectric couples



2011

2021

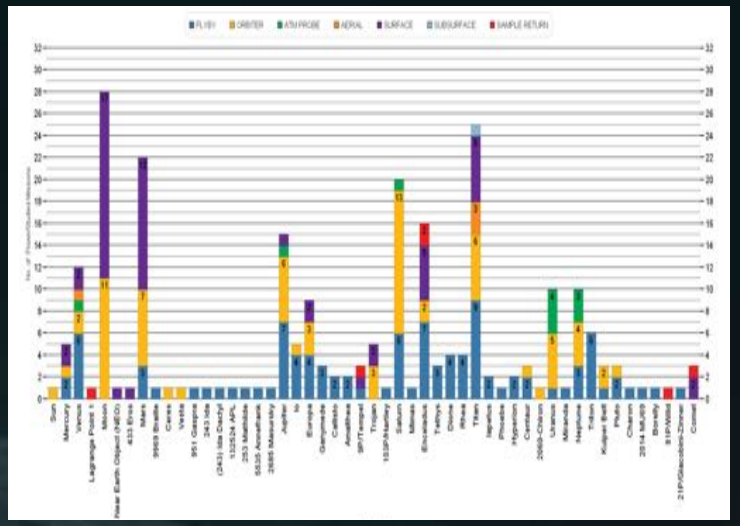
eMMRTG: SKD Technology Maturation Phased Development



Next-Gen RTG: Study Objectives

Determine the characteristics of a Next-Generation RTG that would "best" fulfill Planetary Science Division (PSD) mission needs.

- An RTG that would be useful across the solar system
- An RTG that maximizes the types of potential missions: flyby, orbiter, lander, rover, boats, submersibles, balloons
- An RTG that has reasonable development risks and timeline
- An RTG that has a value (importance, worth and usefulness) returned to PSD that warrants the investment as compared with retaining existing baseline systems



249 Mission Studies in database

67 Candidate TE Technologies

Next-Gen RTG: Key Considerations

- End of mission power
  - Degradation rate
- Integration & Operations
  - Number of generators per mission 4 or less
- Risks to get to a generator
  - TE TRL maturity
  - Generator design heritage
- PSD mission focus in next 10 years (as best aware)
  - Flyby and orbit Outer Planets
  - Land and rove Ocean Worlds

Next-Gen RTG: Requirements Process

Destinations (63)
(Visited or suggested in Decadal Surveys)

Venus | Jupiter "Gas" | Europa "Ocean" | Neptune "Ice"

MMRTG/eMMRTG Req.

GPHS-RTG Req.

	Requirements I (MMRTG, GPHS-RTG)
	Performance
	Physical
	Structural
	Environmental

	Requirements II (Alignment: Destination, Spacecraft/ Mission, Mission Types, Launch vehicles)
	Performance
	Physical
	Structural
	Environmental

	Draft Requirements Tables
	Performance
	Physical
	Structural
	Environmental

Spacecraft/Missions (99) /Mission Types
(Flown and Studied)

Cassini (Orbiter) "Flown"

Venus Rover (Surface) "Suggested"

Titan Submarine (Subsurface) "Suggested"

Launch Vehicles (4)

Titan IV B Launched: Cassini

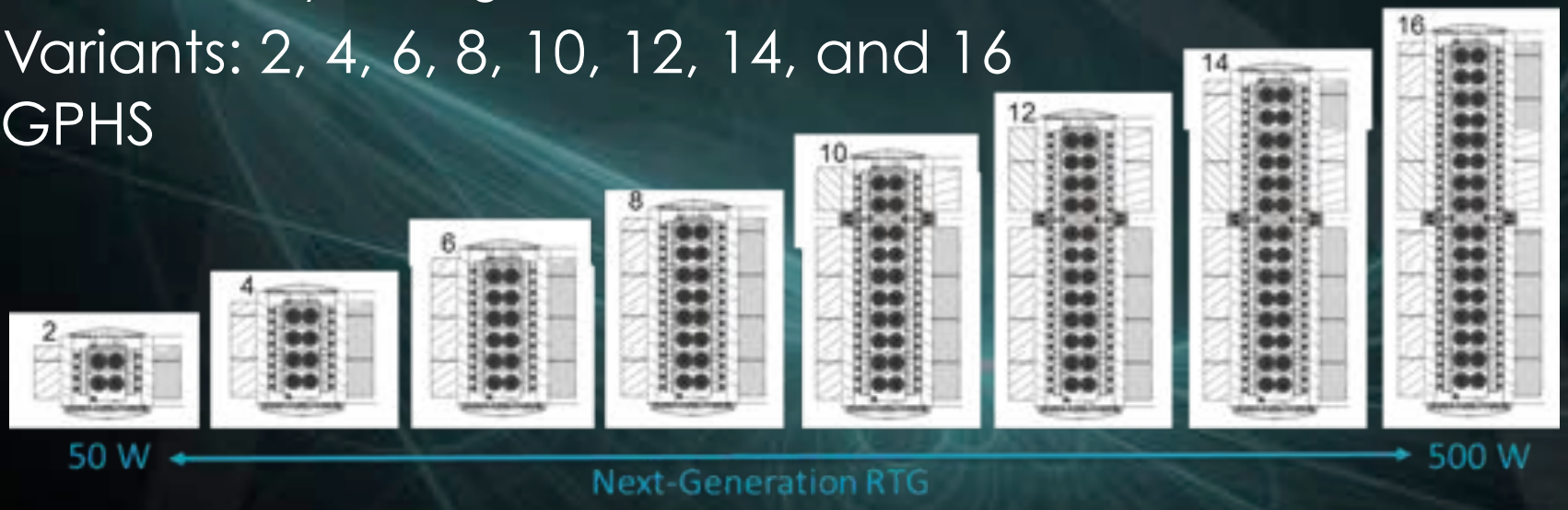
Atlas V (541) Launched: MSL

Delta IV Heavy Potential Launcher

SLS (1 A and B) Potential Launcher

Next-Gen RTG: Concepts

- Types of *new* RTG Concepts:
  - Vacuum Only
    - Segmented (TECs)
    - Cold Segmented
    - Segmented-Modular
    - Cold Segmented-Modular
  - Vacuum and Atmosphere
    - Hybrid Segmented-Modular
    - Cold Hybrid Segmented-Modular
- Variants: 2, 4, 6, 8, 10, 12, 14, and 16 GPHS



Next Gen RTG: Overview of Recommendations

- Complete eMMRTG
  - Continue with skutterudite thermoelectric couple
  - Carry development to eMMRTG Qualification Unit
- Initiate Next-Generation RTG System
  - Vacuum-only
  - Modular
  - 16 GPHSs (largest RTG variant)
  - P_{BOM} = 400-500 W_e (largest RTG variant)
  - Mass goal of < 60 kg (largest RTG variant)
  - Degradation rate < 1.9 %
  - System to be designed to be upgraded with new TCs as technology matures

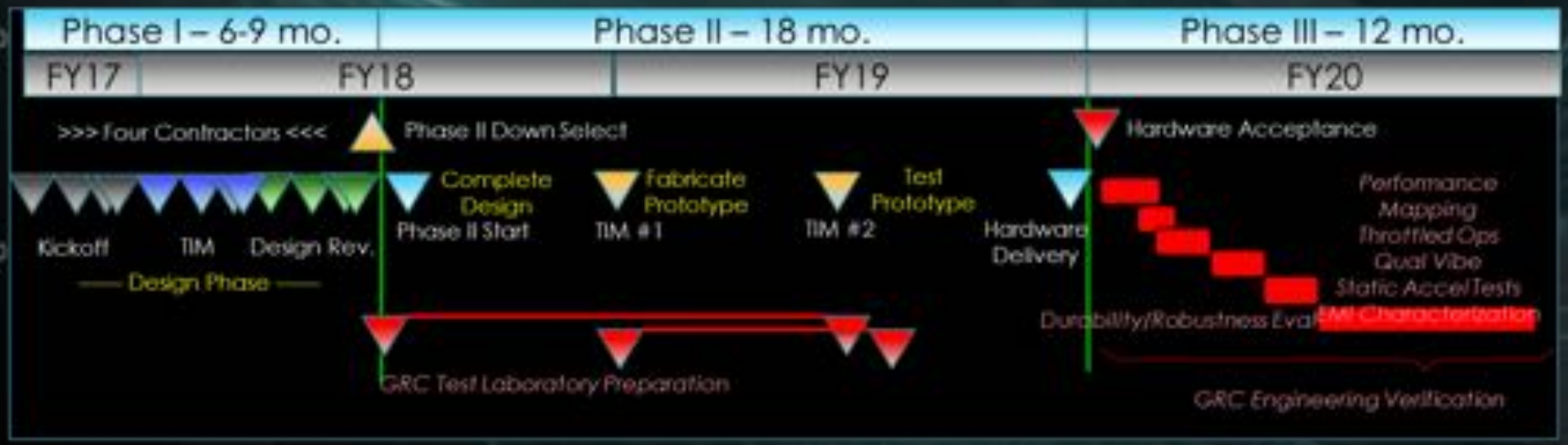
Next-Gen RTG: Plan Forward

- System concept driven TE technology plan
- Technology includes TE technology and associated technology (e.g. insulation)
- JPL materials and TE information to be made available
  - Details being worked
- Three Technology Phases with Gates
  - Phase I Technology Advancement
  - Phase II Technology Maturation
  - Phase III Government evaluation phase
- If technology is deemed mature to proceed – DOE System Development Contract to Qualification unit by 2028

Dynamic Conversion: Plan and Schedule

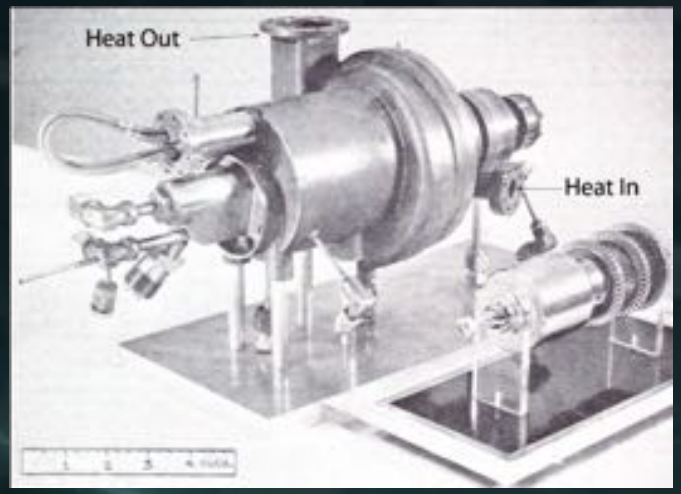
In the context of developing a 200-500 We RPS determine the development readiness and risk associated with dynamic power conversion technologies

- Key conversion technology evaluation characteristics
  - Reliability
  - Robustness
  - Manufacturability
  - Life-cycle and sustainability costs
  - Performance
- Benefits Fission Power Systems development



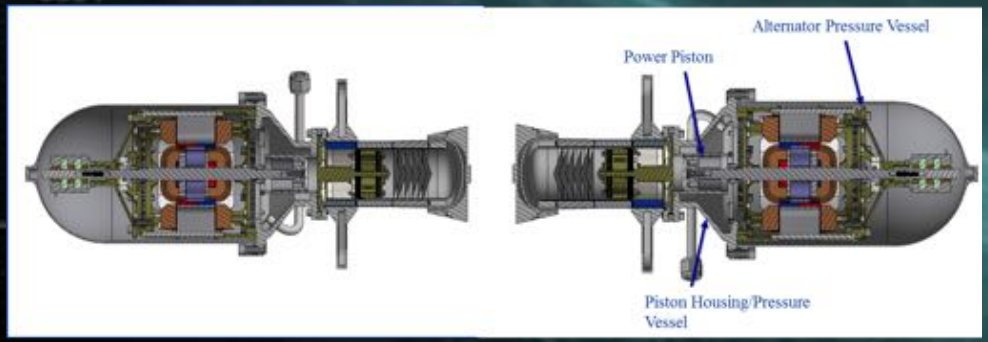
Dynamic Conversion: 4 Contracts

Creare: Turbo-Brayton



Northrop Grumman: ThermoAcoustic Power Convertor (TAPC)

ITC: Free-Piston Stirling Engine (FPSE) Flexure



Sunpower: FPSE Gas Bearing

Summary

- RPS Program and DOE working together to provide NASA a robust, end-to-end program capability
  - Strong NASA & DOE partnership
  - DOE
    - Committed to supporting NASA nuclear missions
    - Actively transforming its customer relationship with NASA to ensure the deliveries of RPS and RHUs
    - Established singular point of contact for all nuclear missions
  - Mission target driven technology development
  - Constant Rate Production
    - Significant cost reductions realized for missions
    - Plutonium Production
      - End-to-End demonstration complete
      - Focused on increasing production rate in phased approach
  - Nuclear Launch Coordination
    - Process optimizations in work, both at NASA and DOE

Power to Explore