U.S. DEPARTMENT OF ENERGY

Nuclear Energy

National Aeronautics and Space Administration

LPSC Community Dialogue:

Usage of Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) for Future Potential Missions

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Lunar and Planetary Sciences Conference

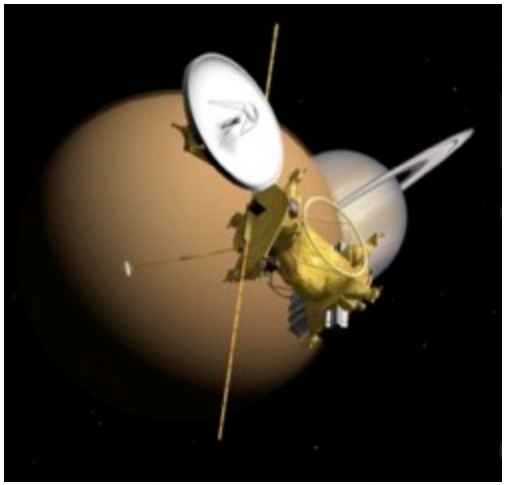
March 23, 2016

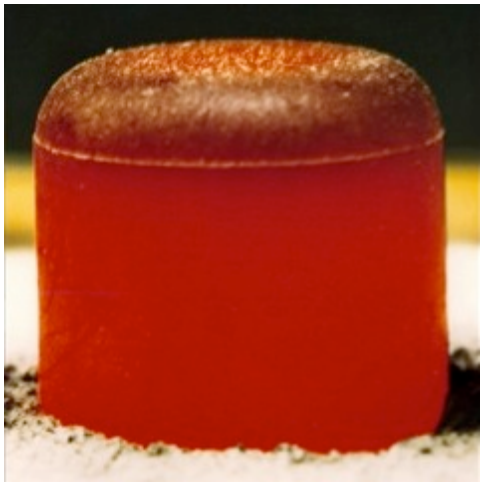
Agenda

- NASA/DOE RPS Background
- MMRTG Technical Information
- RPS considerations
- Supporting future missions
- How to Get Additional Information
- Q&A

Charts will be posted at rps.nasa.gov/usersguide

Radioisotope Power Systems





- Enable and significantly enhance missions by providing electrical power to explore remote and challenging environments where the availability of solar power is limited
  - Spacecraft operation
  - Instrumentation
- Converts heat from a Radioisotope into electricity
  - Heat is the product of the natural decay process of the isotope

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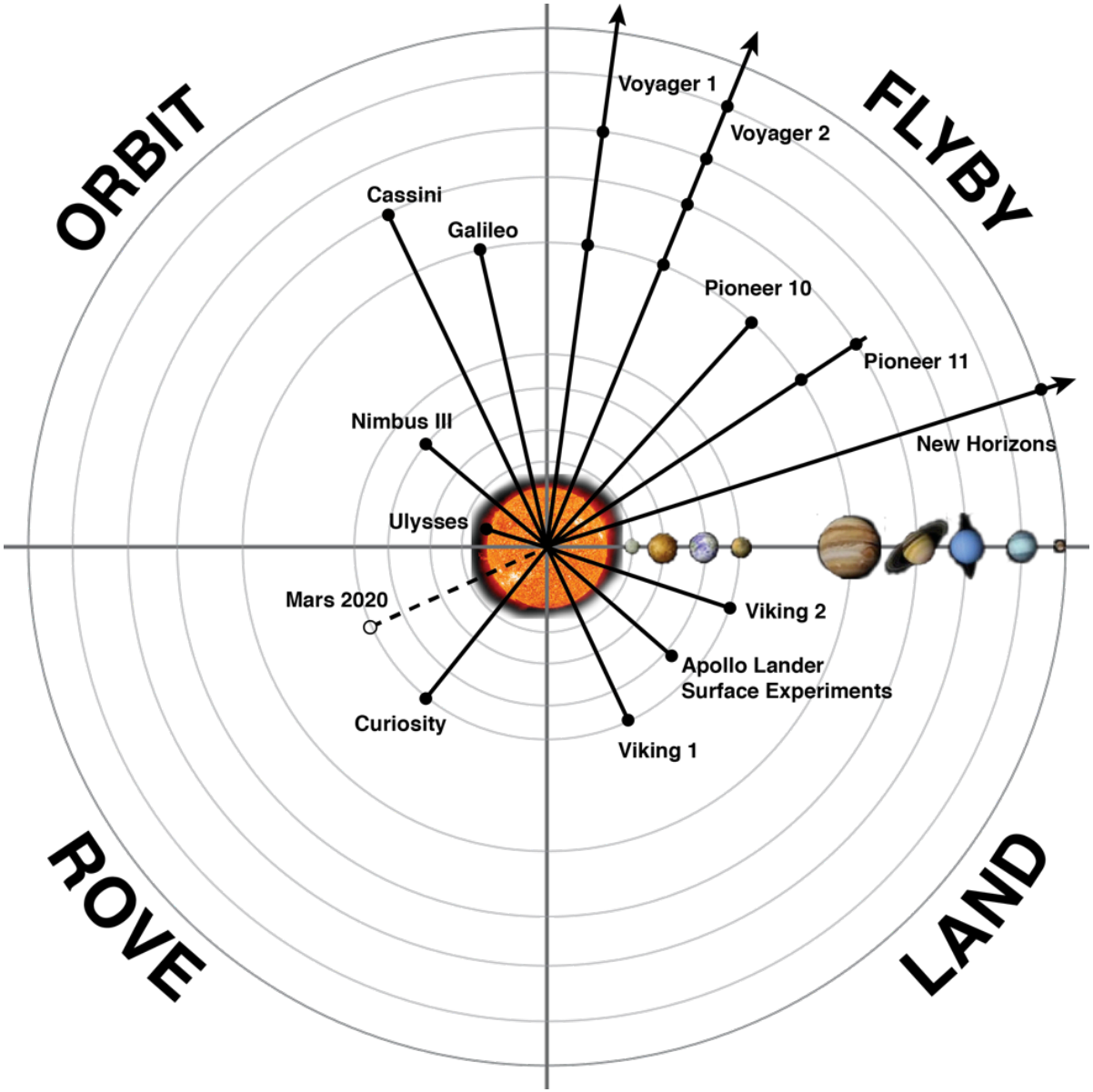
Deployment of Radioisotope Power Systems require joint coordination between **NASA** and **DOE**

Over 50 years of RPS Missions



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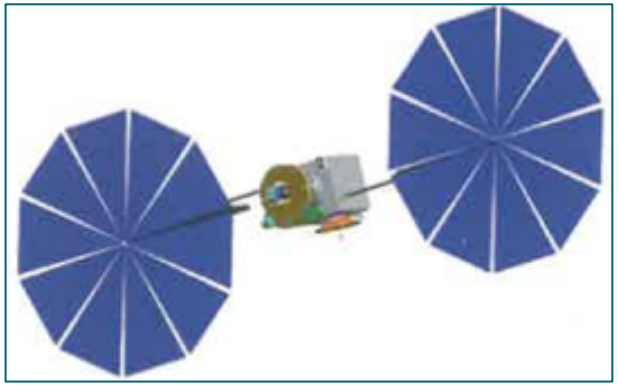
New Frontiers #4 Focused Missions

Comet Surface Sample Return

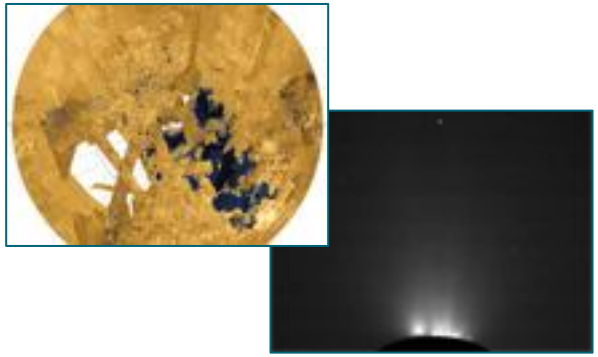


Lunar South Pole Aitken Basin Sample Return

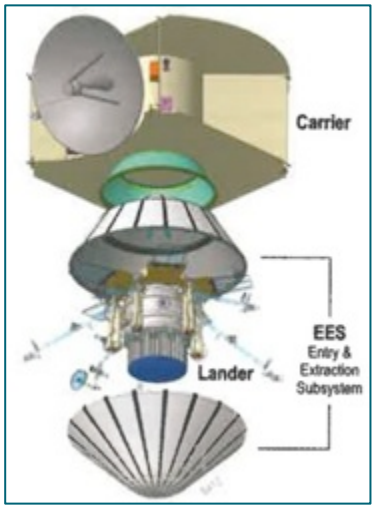
Trojan Tour & Rendezvous

Saturn Probes

Ocean Worlds (Titan And Enceladus)



Venus In-situ Explorer



Courtesy J. Green (HQ); Cassini images

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MMRTG TECHNICAL INFORMATION

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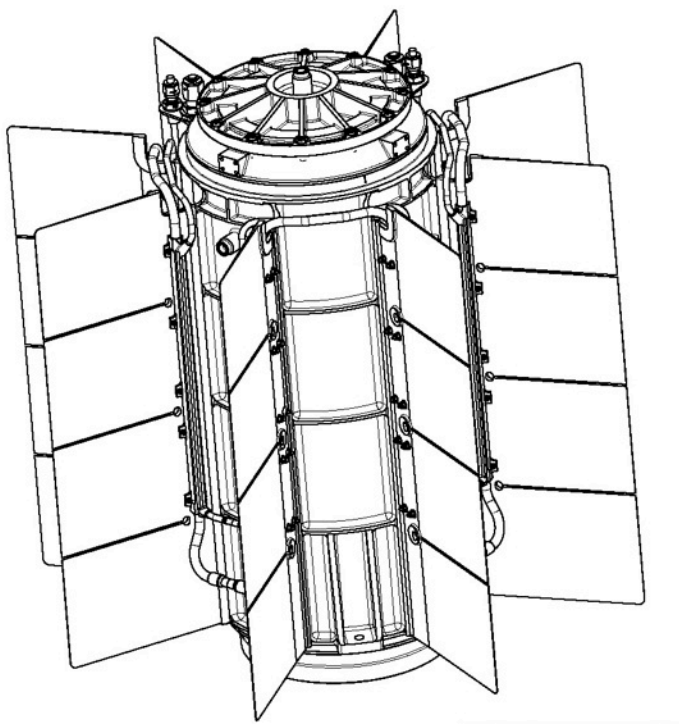
MMRTG Primer

- The Multi-Mission Radioisotope Thermoelectric Generator, or MMRTG, is powering Curiosity and is the baseline power system for M2020 rover.
- *Converts heat produced from the decay of plutonium dioxide into DC power.*

- **Operates in vacuum and planetary atmospheres.**
- **Design is rugged and passive.**
- **Series-parallel electrical circuit for increased reliability.**
- **Does not require in-flight commanding; nor in-flight maintenance.**
- Nuclear Launch Safety basis was established by MSL.



MMRTG

- **Power at launch is >110W DC, quiet.**
- **Mass is ~45kg.**
- **Generator envelope is 65 cm diameter (fin tip-to-tip) x 69 cm height**
- **The environmental requirements include qualification to ATLAS and DELTA LV levels (0.2g^2/Hz.)**
- Thermal output is ~1880Wth, BOL.
- Cooling tubes are optional.
- It mounts using a 4-bolt interface.

As Measured
F1 MMRTG Mass = 44.790 kg

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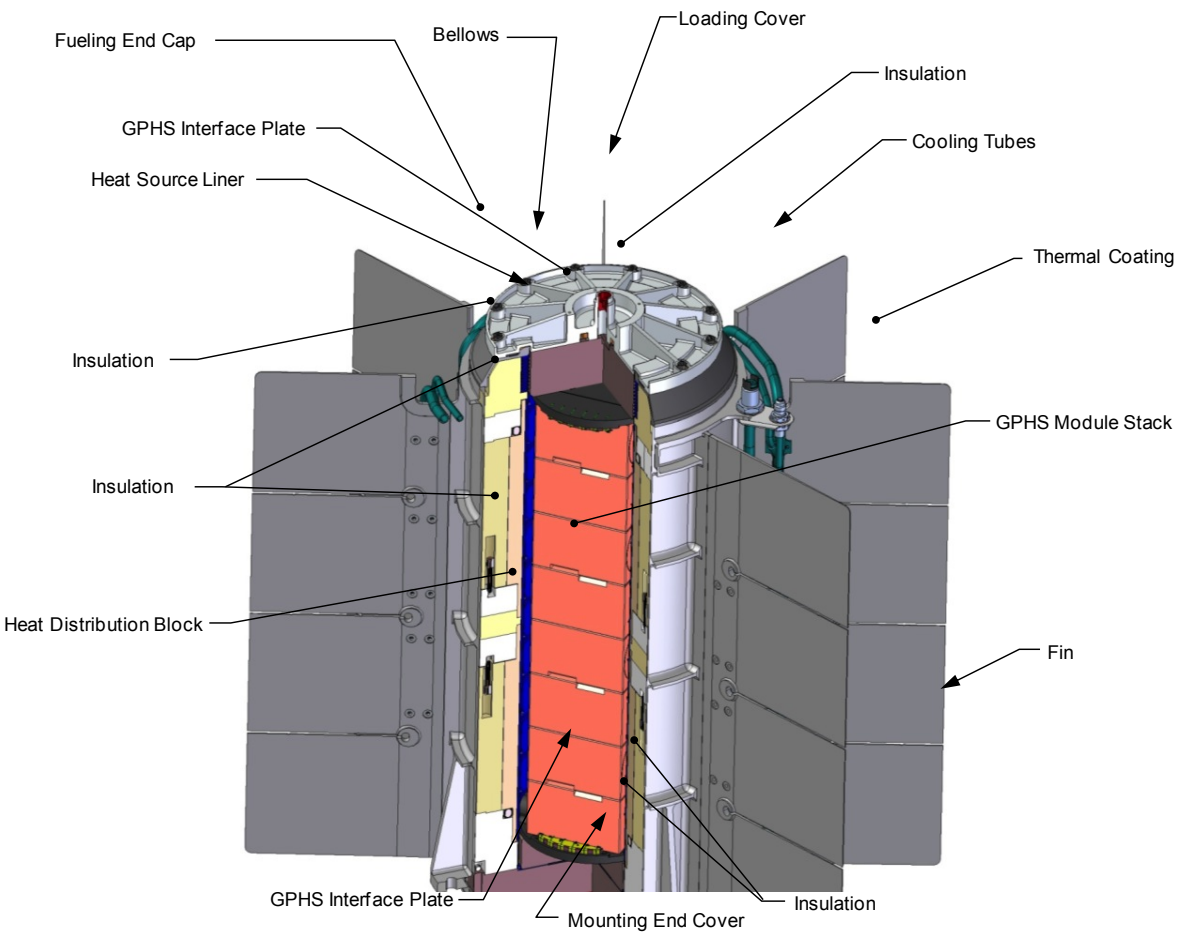
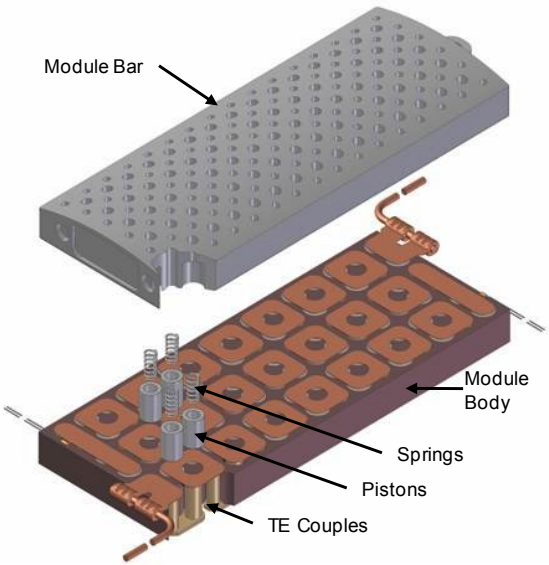
MMRTG Cutaway View





Public Domain Reference:

William Otting, Pratt & Whitney; Leo Gard, Pratt & Whitney; Thomas Hammel, Teledyne Energy Systems, Inc. (TESI); Russell Bennett, Teledyne Energy Systems, Inc. (TESI), "Preparation of the MMRTG for the Mars Science Laboratory Mission"
10th International Energy Conversion Engineering Conference
30-July – 01 Aug 2012, Atlanta, Georgia
Pratt & Whitney is now Aerojet Rocketdyne

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Key Generator Performance Requirements

- MMRTG was designed to multi-mission requirements
- Engineering Unit successfully tested to the multi-mission levels
- F1 was proto-flight tested to the MSL requirements

Item	Multi-mission	MSL
Performance		
Thermal Inventory	244-256 W/GPHS	244-256 W/GPHS
BOM power at 28 V	> 110 W	> 110 W
Load voltage range	22-36 Vdc	22-36 Vdc
Mass	<45 kg	<46.5 kg
Loads		
Random vibration, flight	0.10 g2/Hz	0.03 g2/Hz
Random vibration, qual	0.20 g2/Hz	0.06 g2/Hz
Quasi-static load	30 g	16 g
Pyroshock	6000 g	3000 g
Environment		
Fin root temperature range	50°C to 200°C	50°C to 200°C
Atmosphere	vacuum & atm	vacuum & atm

Public Domain Reference:
MMRTG – Power for the Mars Science Laboratory
Nuclear and Emerging Technology for Space (NETS) Conference
February 26, 2014

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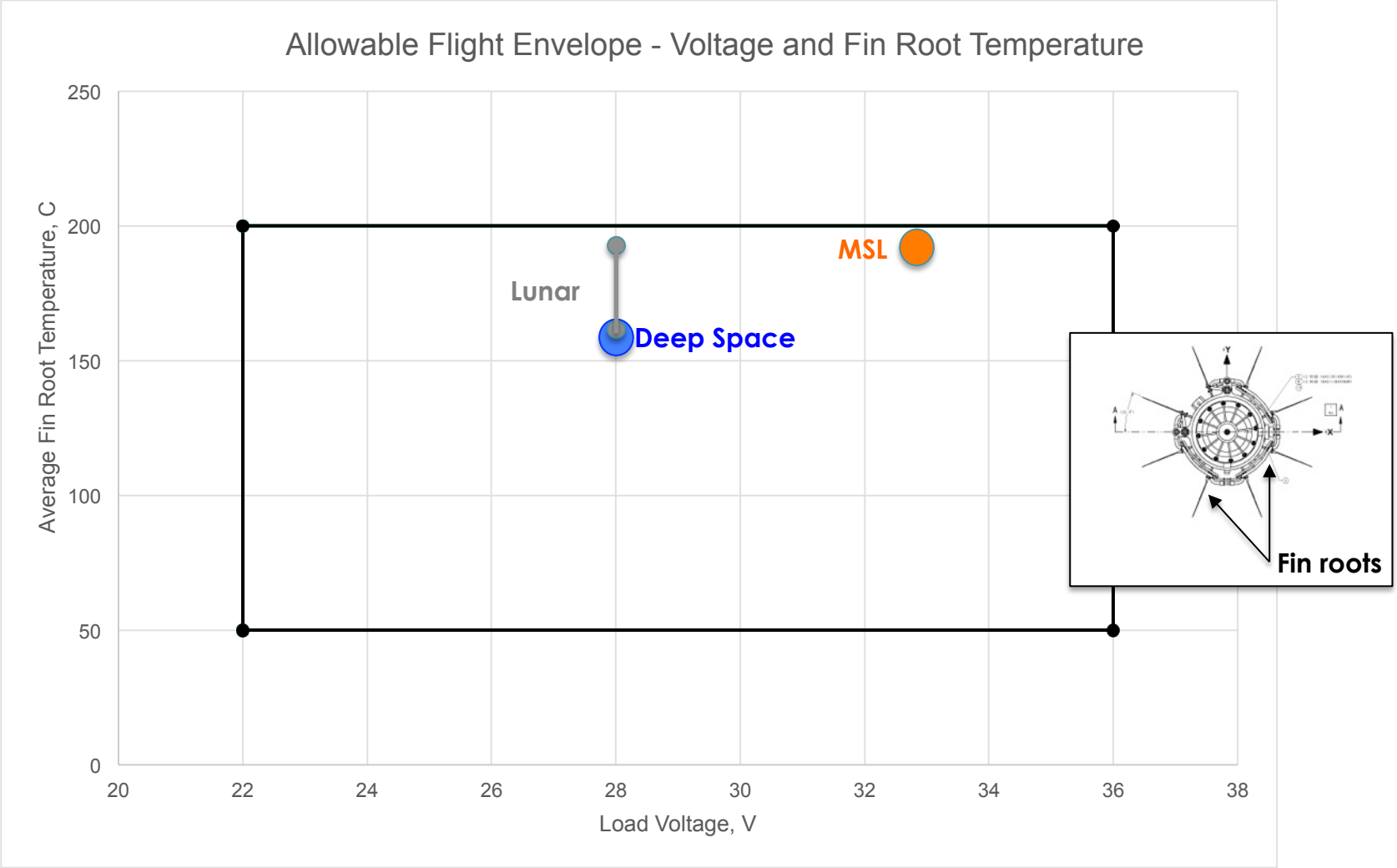
Foundation of Power Estimation Framework; *Allowable Flight Envelope (AFE)*



This envelope should be used by each mission unless special exceptions are negotiated; in other words, each generator is to be designed to provide power throughout this envelope for the design life of the generator, 17 years. Excursions outside of the envelope would likely shorten the life of a generator or threaten components in other ways..

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Caveat Emptor

- The following power predictions are CBEs. Judicious application of margins is the responsibility of the user:
  - An MMRTG degradation rate of 4.8% per year on average is representative of the MSL MMRTG operating on a relatively hot Mars.
  - That is, the MMRTG the degradation rate used for this plot is for an MMRTG operated in the upper right-hand corner of the AFE, see earlier chart. That corner maximizes degradation.
    - Operating at a cooler fin root temperature such as would be experienced during deep space cruise (>3.5 AU from the sun) should lower the degradation rate of the MMRTG, however no degradation data exists for an MMRTG in deep space cruise or in any relatively cool regime.

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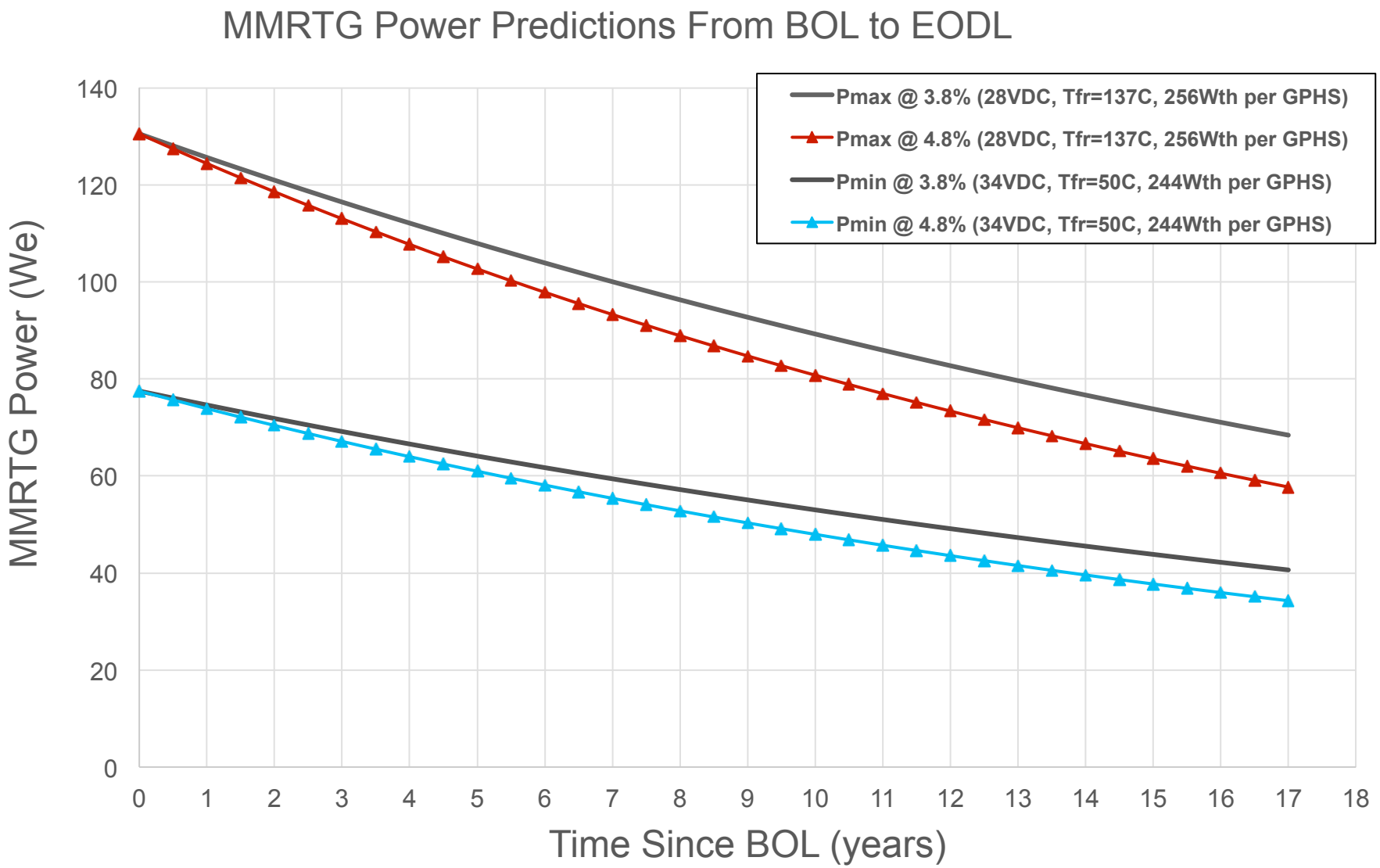
Max/Min Power Envelope



Informational, see MMRTG User's Guide for specific power estimates

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MMRTG User's Guide – MMRTG Technical Data Source

Will be Available in the RPS User's Library in FY2016

MMRTG Technical Data Contained in the User's Guide Includes:

- MMRTG Characteristics
  - Mass
  - Envelope
  - Materials of Construction
- Interfaces
  - Mechanical
  - Electrical
  - Thermal
- Power Generation Characteristics
- Environmental Characteristics
- Life
- Reliability
- Planetary Protection
- Available Ground Support Equipment
- Hardware Models/Simulators
- Available Analytical and CAD Models

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RPS CONSIDERATIONS

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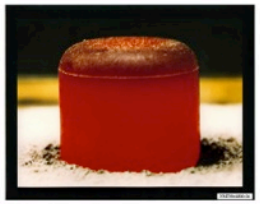
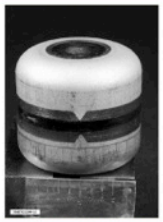
RPS Production Steps

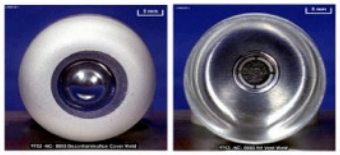
Plutonium Oxide (PuO_2) Fuel Pellet Production
LANL



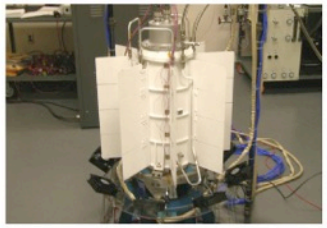
Fuel Pellet Encapsulation
LANL



Iridium Component Fabrication
ORNL



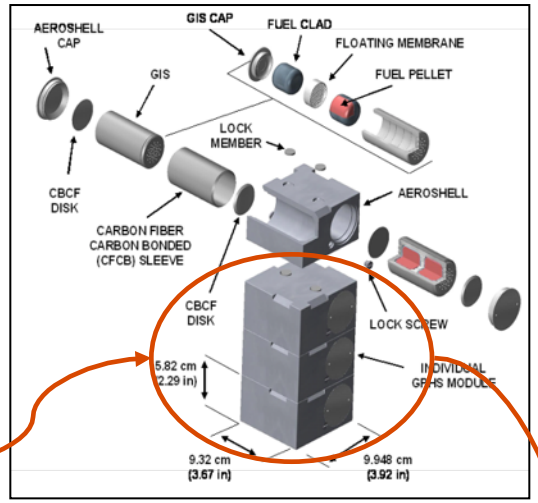
Generator
Design Architect/System Integration Contractor (DA/SIC)



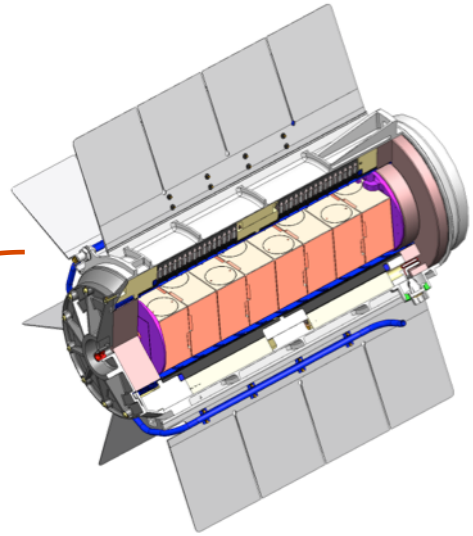
General Purpose Heat Source Module Assembly
INL

RPS Assembly and Testing
INL

RPS Shipment to KSC
INL

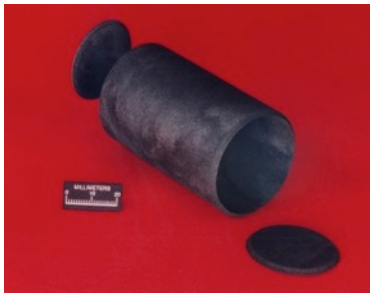


General Purpose Heat Source Module

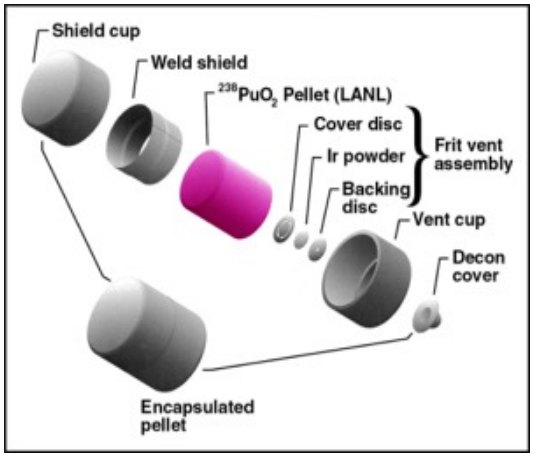


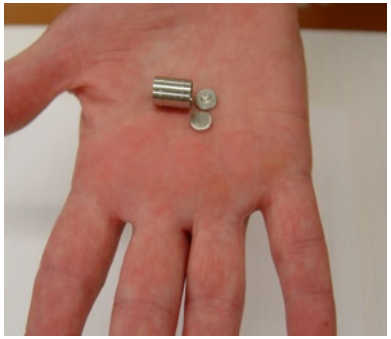
Iridium Hardware and Material Testing Oak Ridge National Laboratory

- Oak Ridge National Laboratory is the lead materials development laboratory



- Specific capabilities:
  - Iridium alloy encapsulation hardware production
  - Manufacture of Carbon Bonded Carbon Fiber (CBCF) insulation
  - Unique materials testing capabilities
  - Manufacture Light Weight Radioisotope Heater Unit (LWRHU) components





- ORNL also leads project to reestablish domestic supply of Pu-238

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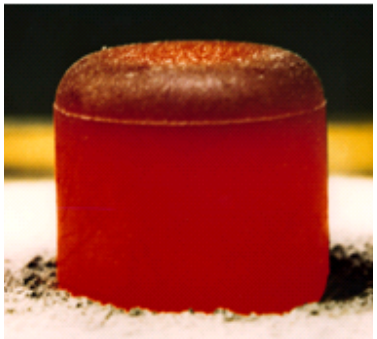
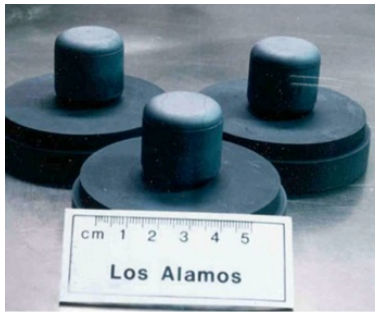
Heat Source Production
Los Alamos National Laboratory

- LANL maintains capability for Pu-238 oxide processing and fueled clad fabrication
- Specific Capabilities:
  - Purification of Pu-238 (scrap recovery)
  - Pelletization of purified Pu-238
  - Encapsulation of Pu-238 pellet
  - Impact testing for safety verification
  - Metallography
  - Chemical analysis
  - Nuclear material storage and security
  - Waste handling and disposal





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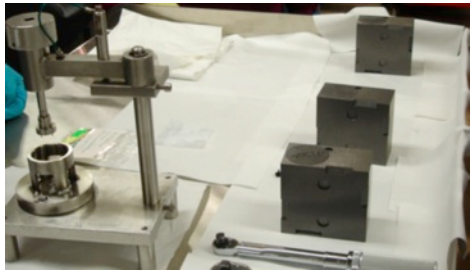
Power System Assembly, Testing and Delivery – Idaho National Laboratory

- INL maintains capability for RPS assembly, testing, storage, and delivery of radioisotope power systems
- Specific capabilities:
  - Material procurement and component fabrication
  - Heat source module assembly
  - RPS assembly
  - RPS acceptance testing
  - Specialized transportation systems
  - Delivery of RPS to customers
  - Ground support at customer site, including standing up temporary DOE nuclear facilities
- INL serves as the Technical Integration Office and Lead Laboratory for quality assurance



Nuclear Safety and Security at the Launch Site

- Stand up temporary nuclear facilities under DOE jurisdiction per 10CFR830
- DOE indemnifies launch of a nuclear payload
- Prepare Documented Safety Analysis (DSA) for KSC facilities
  - DSA covers operations between arrival at KSC and positioning of the RPS on upper deck of building housing rocket
- Conduct operations of DSA through USQ process involving work in DOE-KSC nuclear facilities
- The Safety Analysis Report for launch covers operations, beginning with from final integration with the spacecraft

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KSC Ground/Launch Support

- Wellness check of RPS unit
- Hot fit check with spacecraft / rover
- Final dry run at Vertical Integration Facility (VIF)
- Integrate with spacecraft at VIF

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Nuclear Launch Safety

- Safety is an essential factor in the design of all space nuclear power systems
- Launch vehicle and spacecraft failures DO occur and those failures result in unique and highly energetic accident environments
- Space nuclear power systems must be developed with these accident scenarios in mind to prevent or minimize the amount of nuclear materials released into the biosphere
- A rigorous safety analysis is conducted by DOE on all power systems and missions to determine the risk drivers so that corrective or mitigating actions can be taken to reduce the risk to people and the environment

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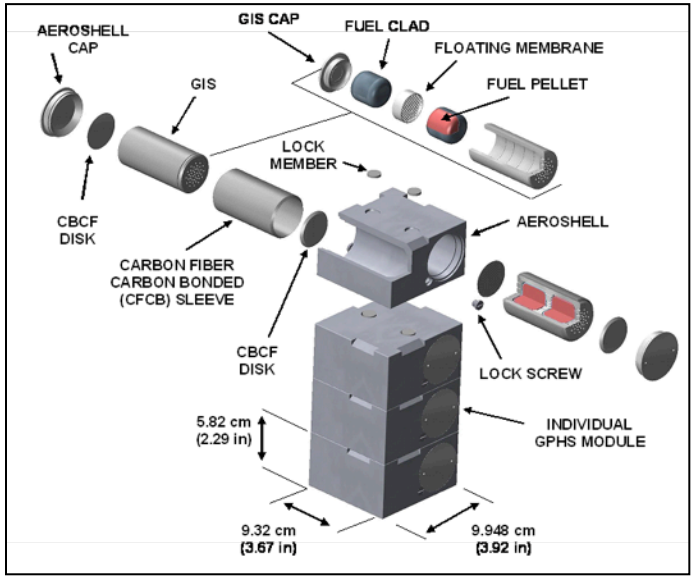
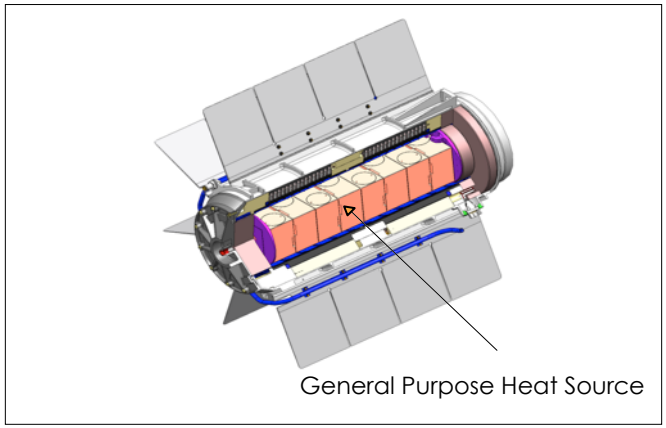
Key Components and Safety Features

- Pu-238 fuel (generates decay heat)
  - Alpha-emitter, 87-year half life
  - High melting temperature (2,400°C / 4,352°F)
  - Fractures into largely non-respirable chunks upon impact
  - Highly insoluble in water
- Cladding (encases the fuel)
  - Fuel containment (normal operations or accidents)
  - High melting point – thermal protection (2,454°C / 4,450°F)
  - Ductile – impact protection
- Graphite heat source (protects fuel & cladding)
  - Impact shell – impact protection
  - Insulator – protect clad during reentry
  - Aeroshell – prevent burnup during reentry
- Converter (converts heat to electricity)
  - Designed to release individual aeroshell modules in cases of inadvertent reentry (minimizes terminal velocity)
- Radiator (rejects excess heat)



General Purpose Heat Source Module



Radioisotope Thermoelectric Generator

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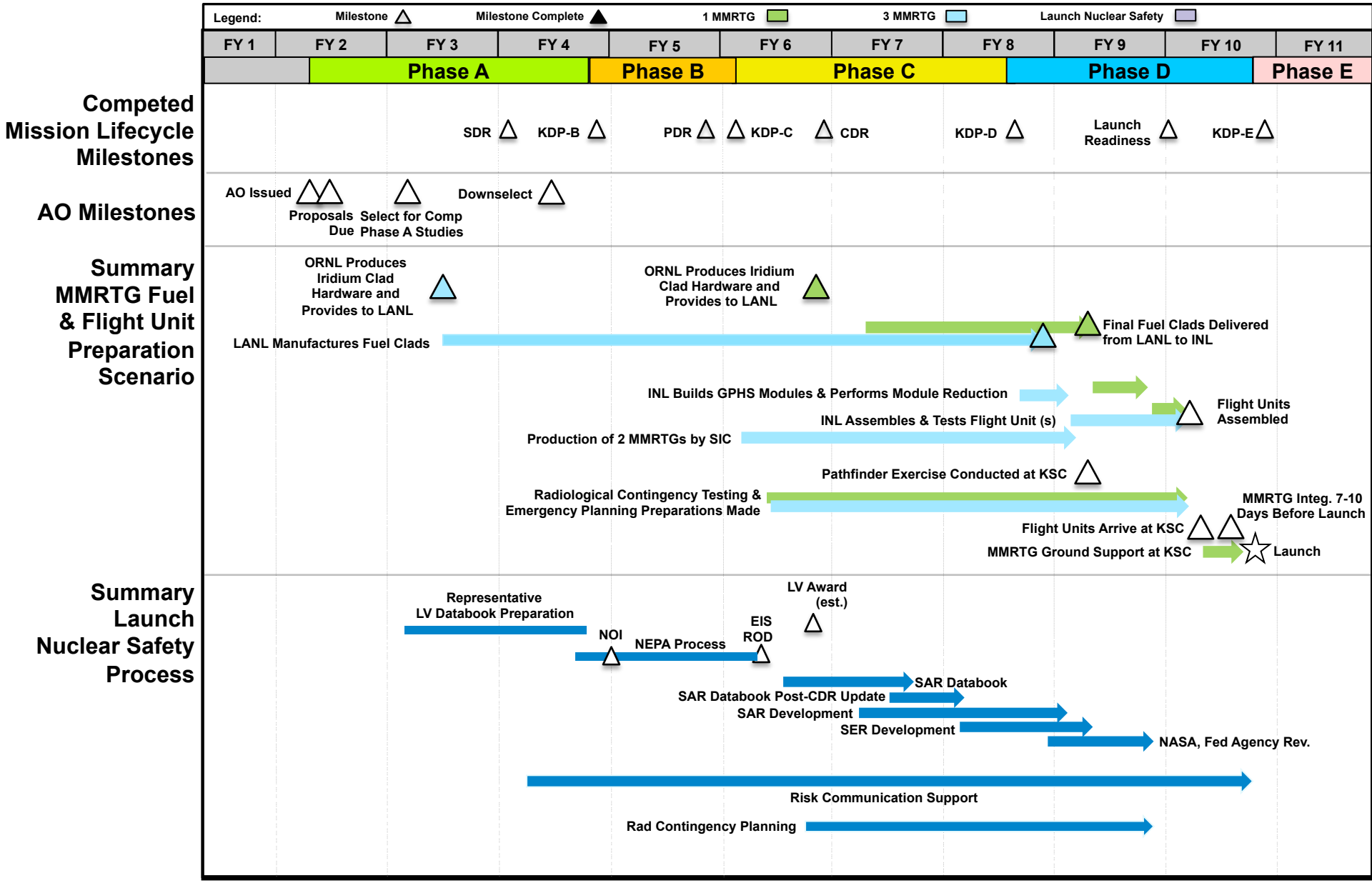
Significant MMRTG-Related Mission Development Milestones



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RPS Cost for Projected 2025 Mission

RPS Type and Quantity	Cost to Fuel & Launch System ($M)	Additional Cost for LSP ($M)	Additional Cost ($M)	Total ($M)
RPS & RHU Missions				
1 MMRTG	105	28	0	133
2 MMRTG	135	28	0	163
3 MMRTG	165	28	0	193
1 MMRTG + RHU (Quantity < 43)[1]	105	28	2[2]	135
2 MMRTG + RHU (Quantity < 43) [1]	135	28	2[2]	165
3 MMRTG + RHU (Quantity < 43) [1]	165	28	2[2]	195
1 MMRTG + RHU (Quantity >43 and < 190)	105	28	34[3]	167
2 MMRTG + RHU (Quantity>43 and < 190)	135	28	34[3]	197
3 MMRTG + RHU (Quantity >43 and < 190)	165	28	34[3]	227
RHU ONLY Missions				
Quantity < 43	24	21	2	47
Quantity >43 and < 190	24	21	34[3]	79

1. Currently, 43 units are available. All are near 0.89 W_{th}
2. Cost to prepare and use RHUs
3. A new campaign would be needed for new RHUs. ($34M) The costs for that campaign are included in the above numbers.

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SUPPORTING FUTURE MISSIONS

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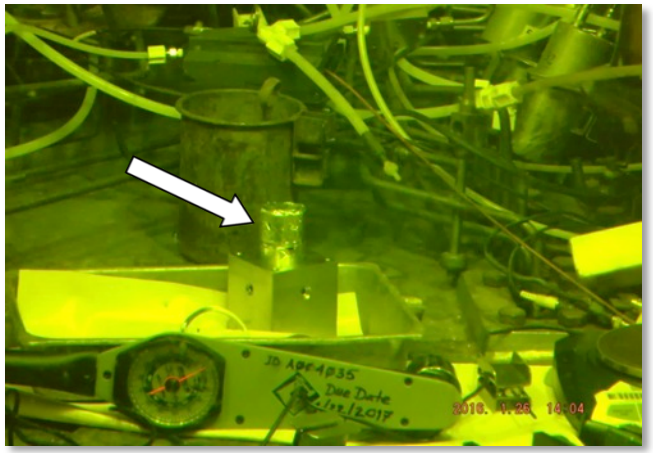
Pu-238 Supply Project Successes

- First new US Pu-238 production since the late 1980s
  - ~ 50 gm total Pu-238 was produced
  - A small sample has been shipped to LANL to compare analytical results
- Successful Preliminary Design Review held in December
- Target production already well underway for second demonstration
  - Goals are to demonstrate larger batch sizes, make any changes/ optimization indicated from first demo and improve operational throughout predictions
- The first shipment of NpO_2 from INL to ORNL has occurred in November



Inner container holds ~ 5g PuO_2

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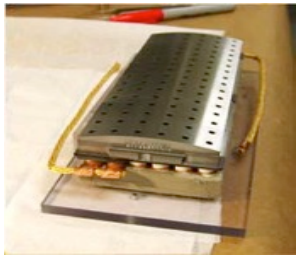
Potential for Higher Efficiency Systems

- Higher efficiency thermoelectrics – eMMRTG
  - Goal is to insert new technology into a flight proven system
  - Upgraded thermoelectric materials developed and demonstrated at JPL
  - Other minor design changes to increase operating temperature
  - With minimal risk to existing MMRTG design, eMMRTG could provide:
    - 21 to 24% BOM power boost over MMRTG
    - EOM improvements are also expected (>40%)

Skutterudite (SKD) materials



Advanced SKD MMRTG modules

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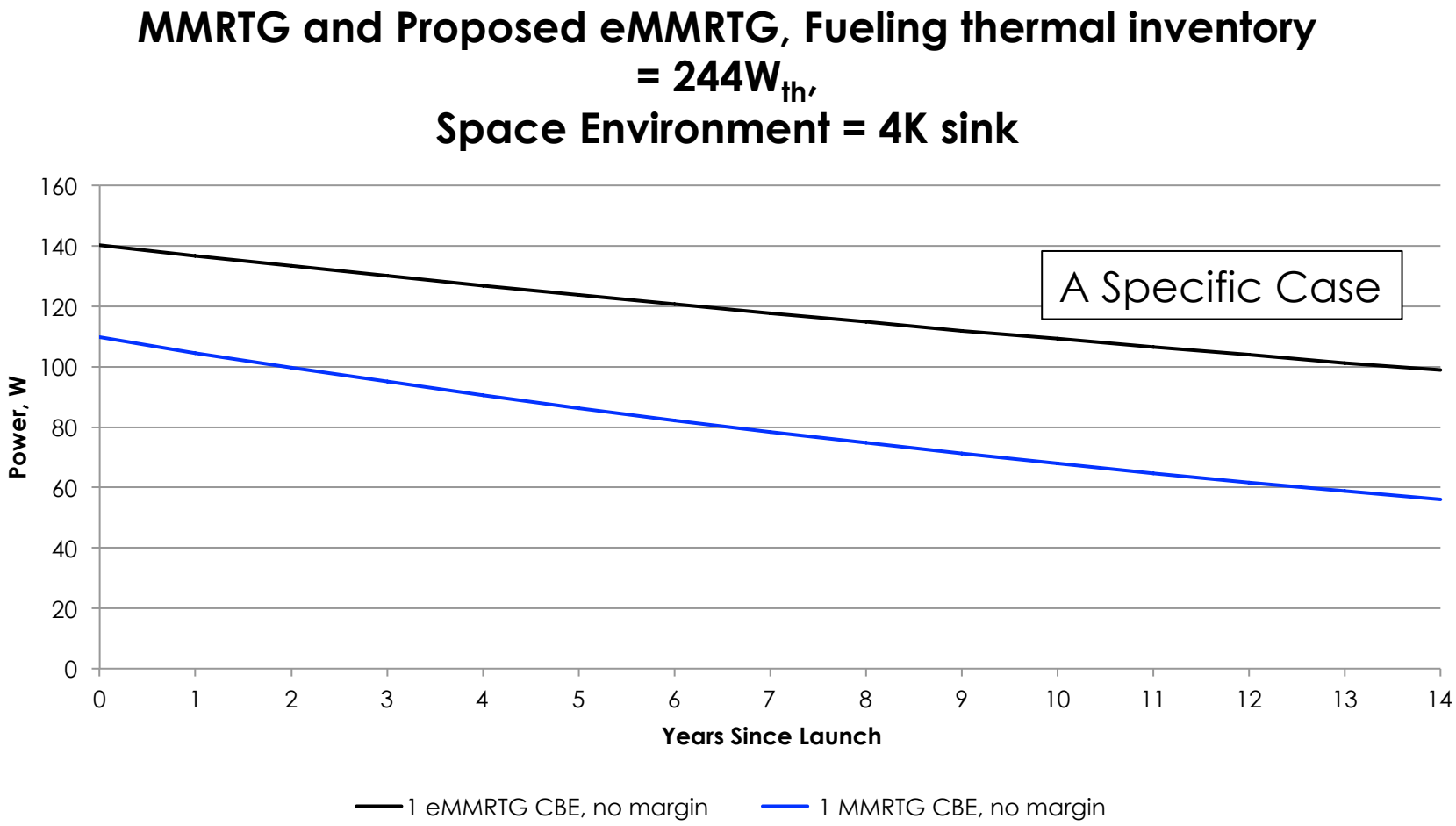
Potential for Higher Efficiency Systems



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HOW TO GET ADDITIONAL INFORMATION

RPS User's Library Summary

- A RPS User's Library is being developed
- **U.S. Citizens** may request approval to access the RPS User's Library
- Library will be an access-restricted database of detailed MMRTG technical data, including:
  - MMRTG User's Guide
  - Test Reports (select)
- Working through process to grant access
- *Only* ***one individual per organization*** *will be granted access to the repository*.
  - The definition of "organization" is subject to the discretion of the RPS Program and DOE

Access Request

- For organizations requesting access submit contact email at rps@nasa.gov using **Subject line labeled: MMRTG User's Guide**
- **Please provide in body of email:**
  - First, Last Name
  - Organization/Employer
  - Role
  - Citizenship
  - Contact email
  - Contact phone
  - Statement of Purpose for Library Access

Questions?

email - rps@nasa.gov

rps.nasa.gov