U.S. DEPARTMENT OF ENERGY
Nuclear Energy

National Aeronautics and Space Administration

New Frontiers 4 Technology Workshop

Radioisotope Power Systems

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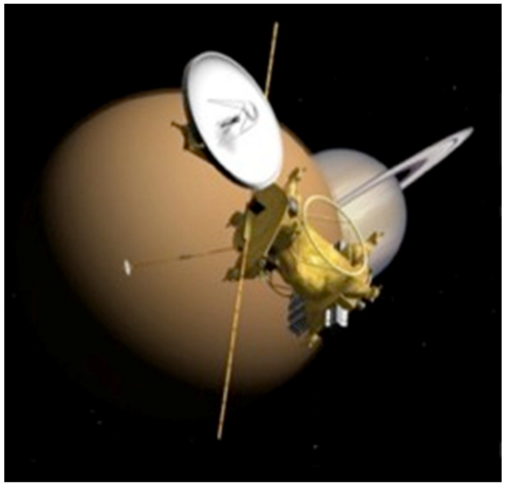
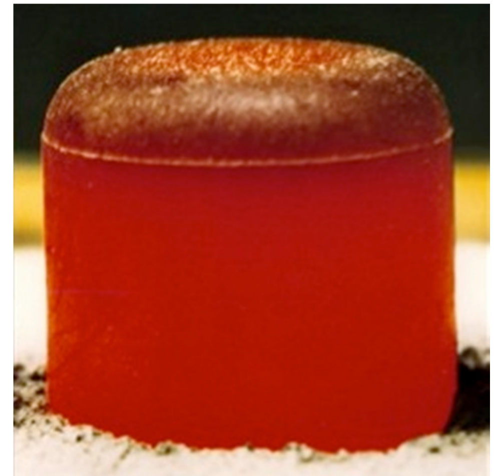
Agenda

- NASA/DOE RPS Background
- Technical Information
  - MMRTG
  - eMMRTG
  - LWRHU
  - RPS considerations
- How to Get Additional Information
- Q&A

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

Radioisotope Power Systems

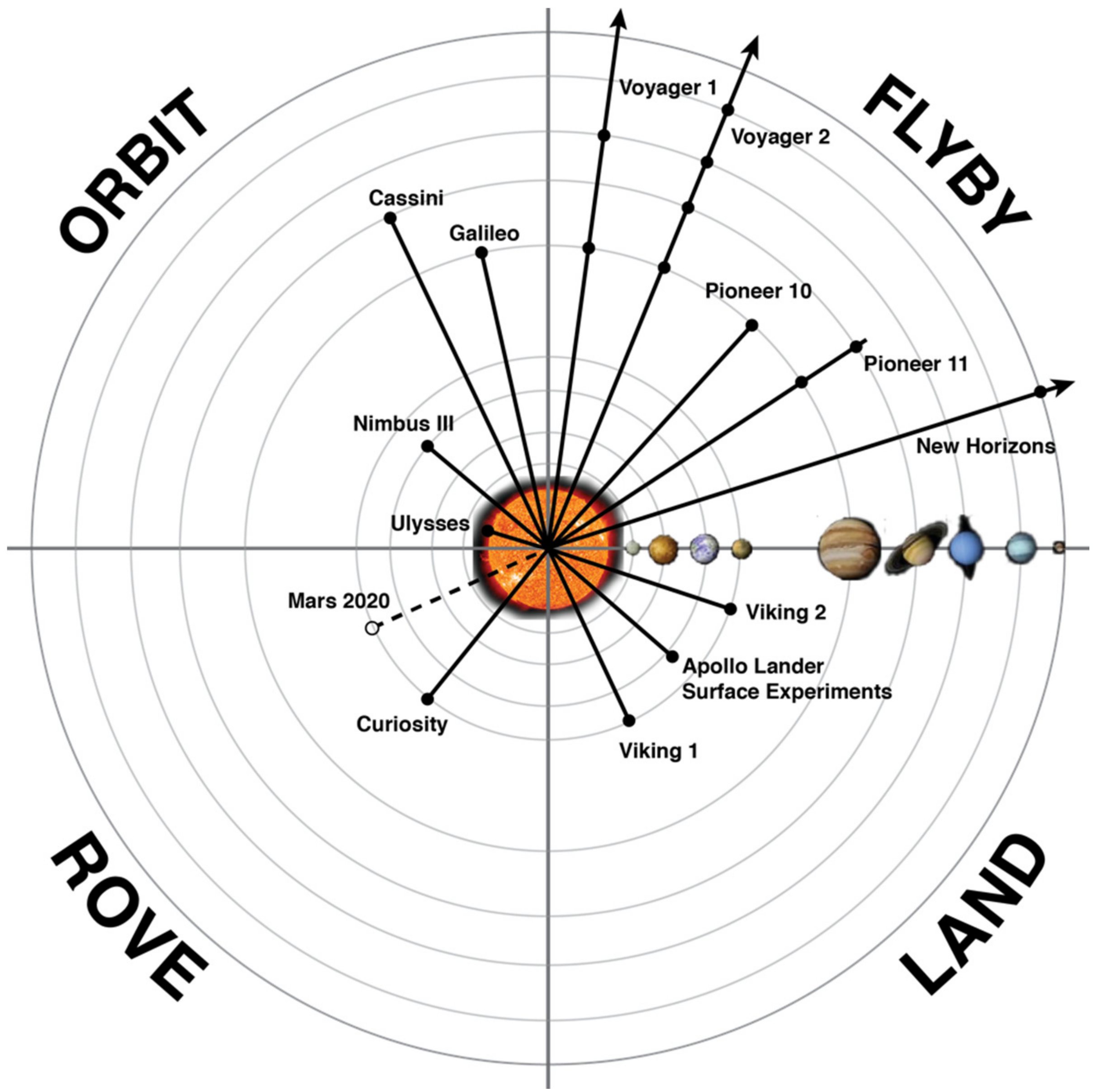




- Enable and significantly enhance missions by providing electrical power to explore remote and challenging environments where the availability of solar power is limited
  - Spacecraft operation
  - Instrumentation
- Converts heat from a Radioisotope into electricity
  - Heat is the product of the natural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

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

Over 50 years of RPS Missions



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TECHNICAL INFORMATION

RPS Assumptions and Constraints

- Definitions
  - Beginning of Life (BOL) is defined as time of fueling
  - Beginning of Mission (BOM) is defined as Launch, and can be as long as 3 years after BOL
  - End of Design Life (EODL) is 17 years after BOL
- Heat Source
  - Step-2 GPHS, estimated at 244-256 W_t at BOL will be used for this study

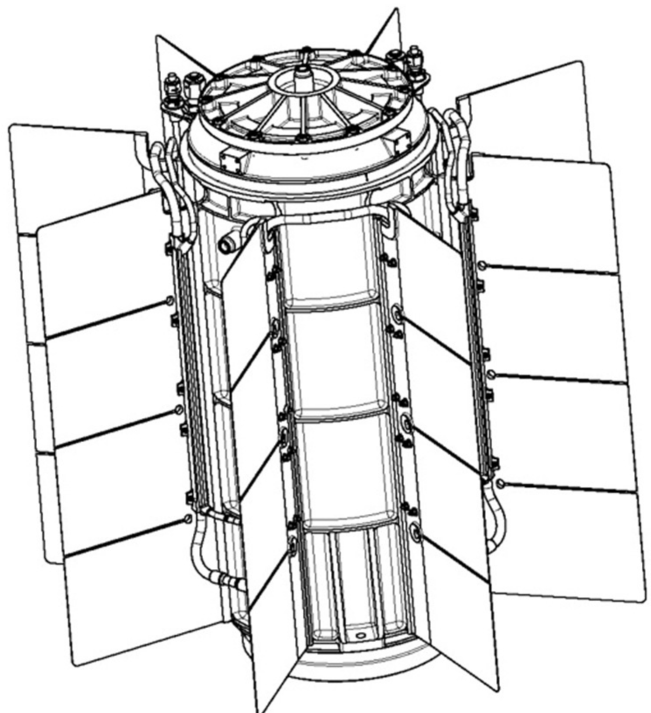
RPS Assumptions and Constraints

- Assembly, Test, Launch and Operations (ATLO)
  - RPS units should be mounted so they can be installed through doors in existing launch fairing, other considerations increase complexity and costs
  - Existing DOE facilities are used for fueling, testing, transportation and storage
- RPS impacts on spacecraft and on instruments
  - Radiation
    - Radiation could have noise effects on instrument measurements, and long-term effects of instrument damage
      - Gamma dose on order of 1 krad over 10 years with 1-meter separation (see next chart)
      - Neutron fluence on order of 6E10 1 MeV n/cm^2 over 10 years with 1-meter separation (see next chart)
  - Thermal
    - RPS produces estimated at 244-256 W_t at BOL $_t$/GPHS that must be considered during spacecraft and instrument design and integration
    - Instrument pointing/field-of-view may be constrained

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.

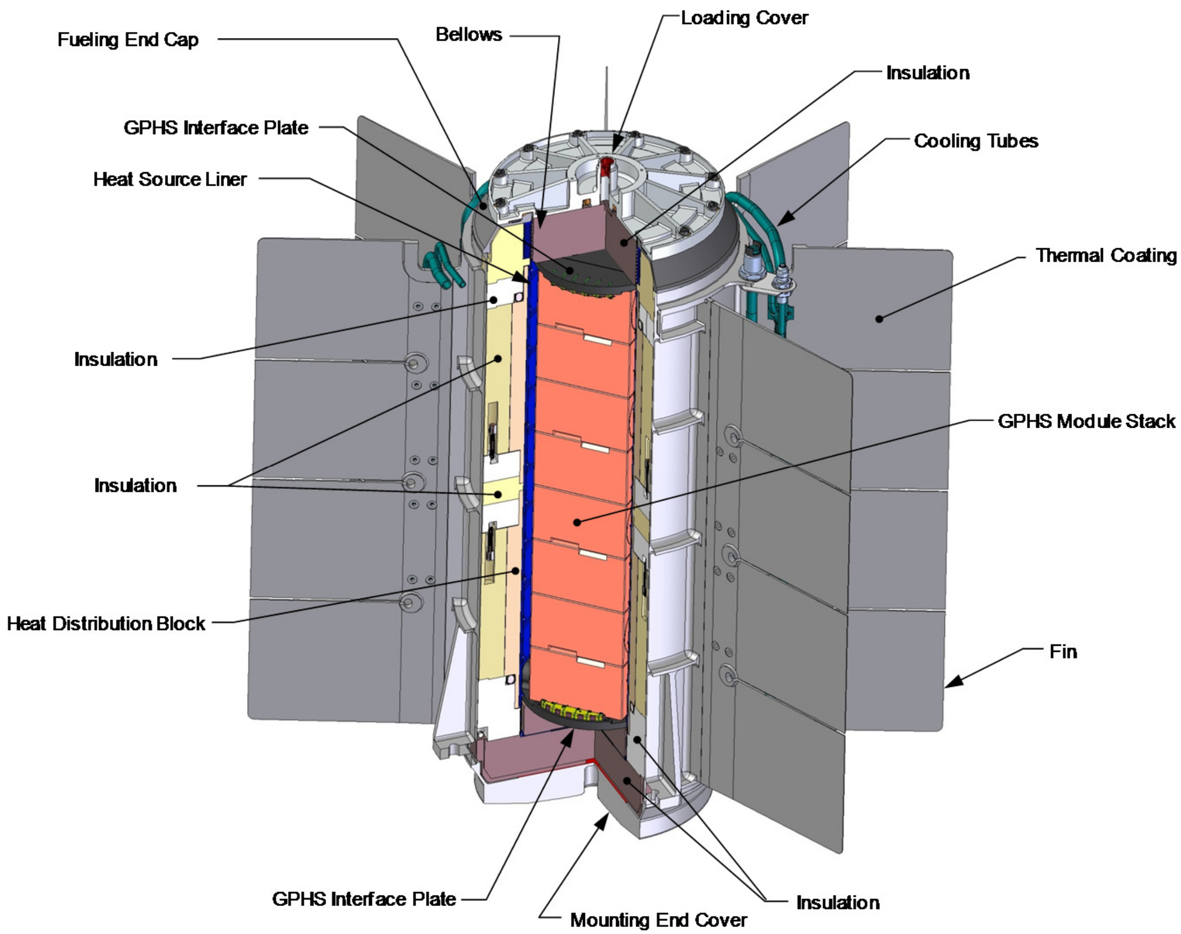


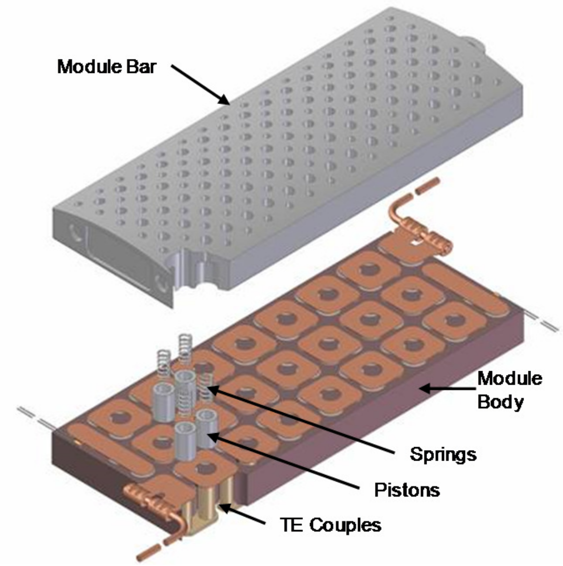
MMRTG

- **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 ~1952Wth, BOL.
- Cooling tubes are optional.
- It mounts using a 4-bolt interface.

As Measured
F1 MMRTG Mass = 44.790 kg

MMRTG Cutaway View





<u>Public Domain Reference:</u>
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

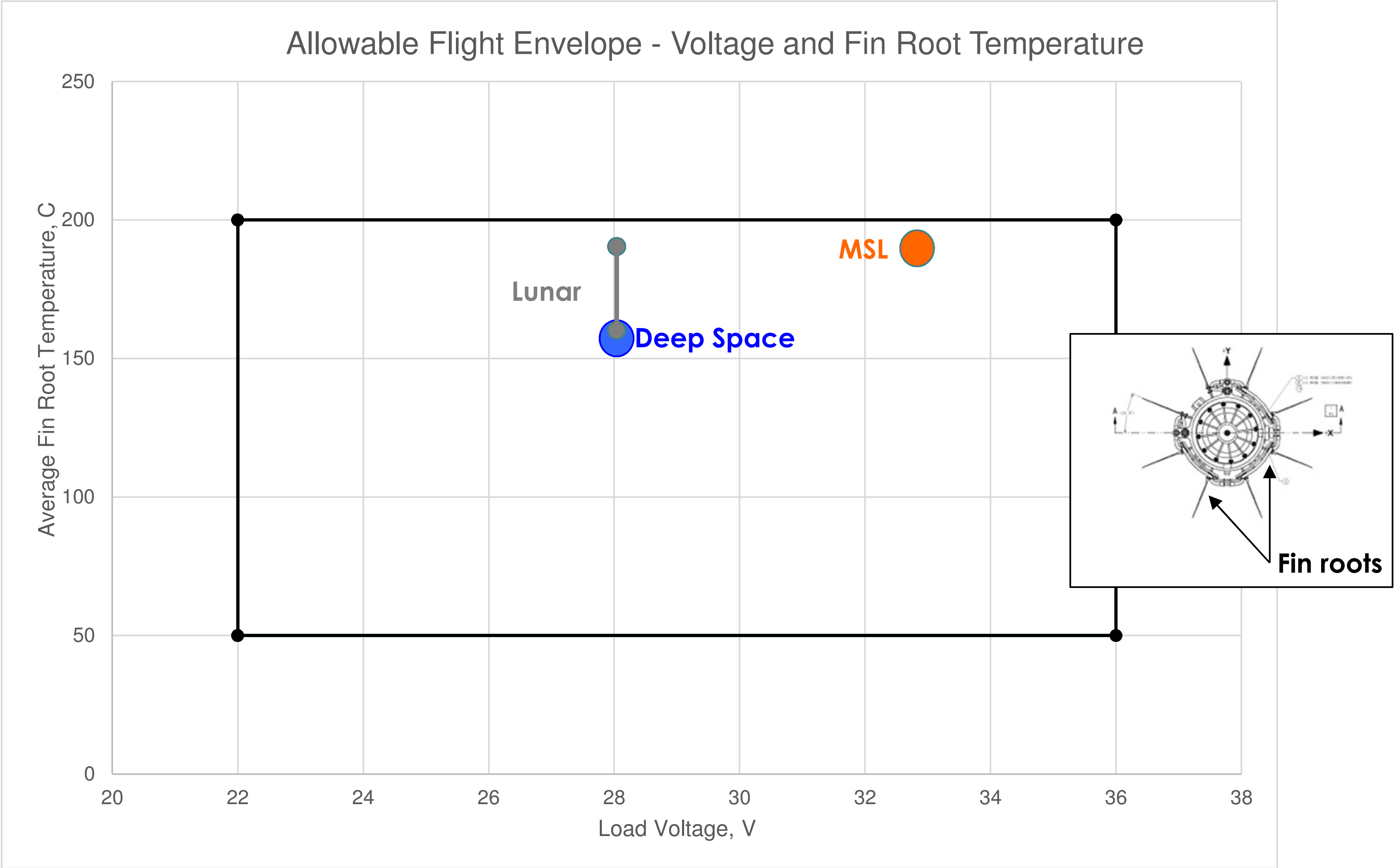
Key Generator Performance Requirements

- 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

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

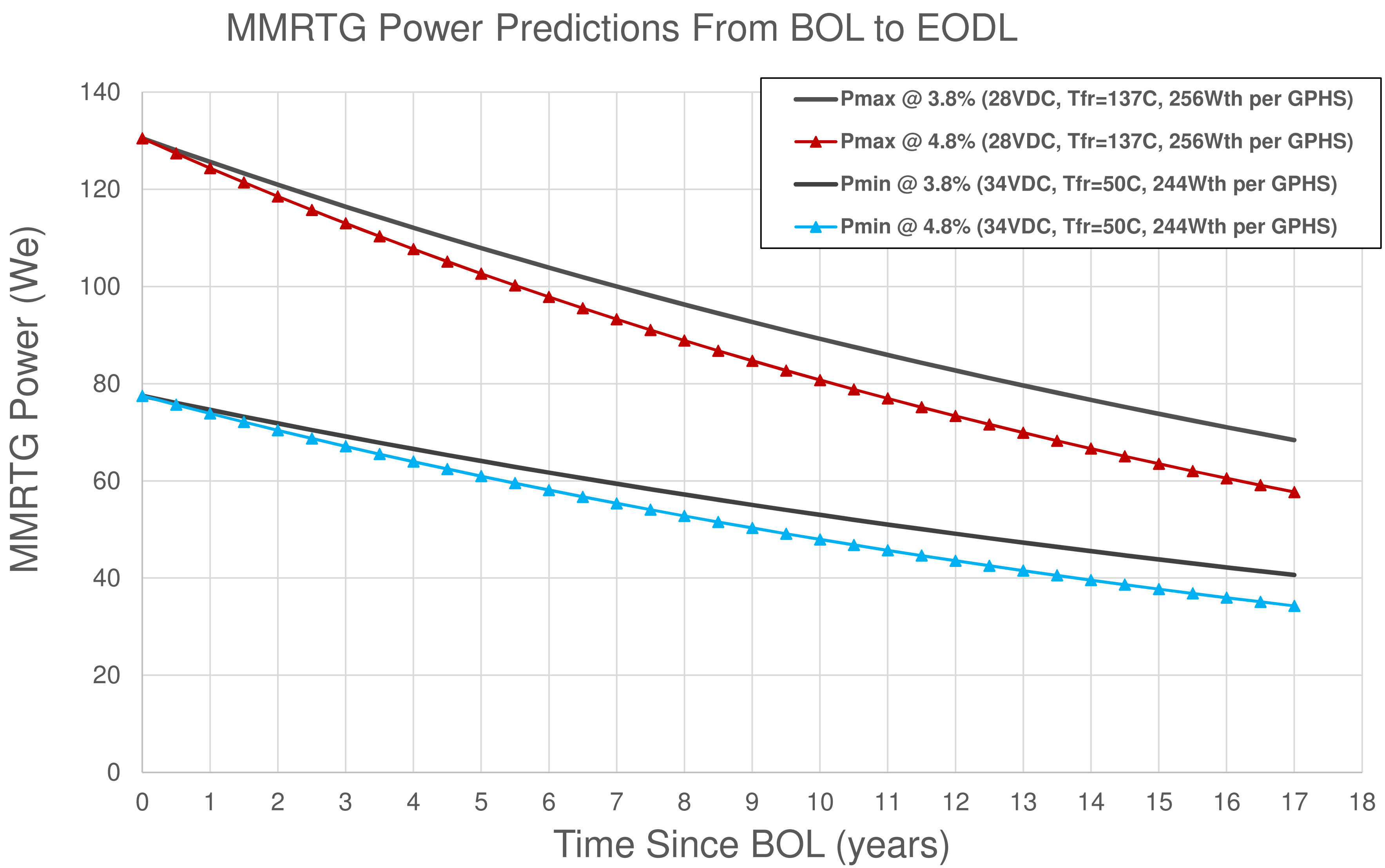


This envelope should be used by each mission unless special exceptions are negotiated; in other words, each generator is to be designed to provide power throughout this envelope for the design life of the generator, 17 years. Excursions outside of the envelope would likely shorten the life of a generator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

Considerations

- 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.

Max/Min Power Envelope



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

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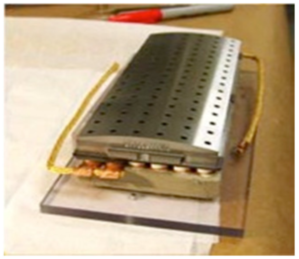
Potential for Higher Efficiency Systems

- 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

eMMRTG Configuration Concept

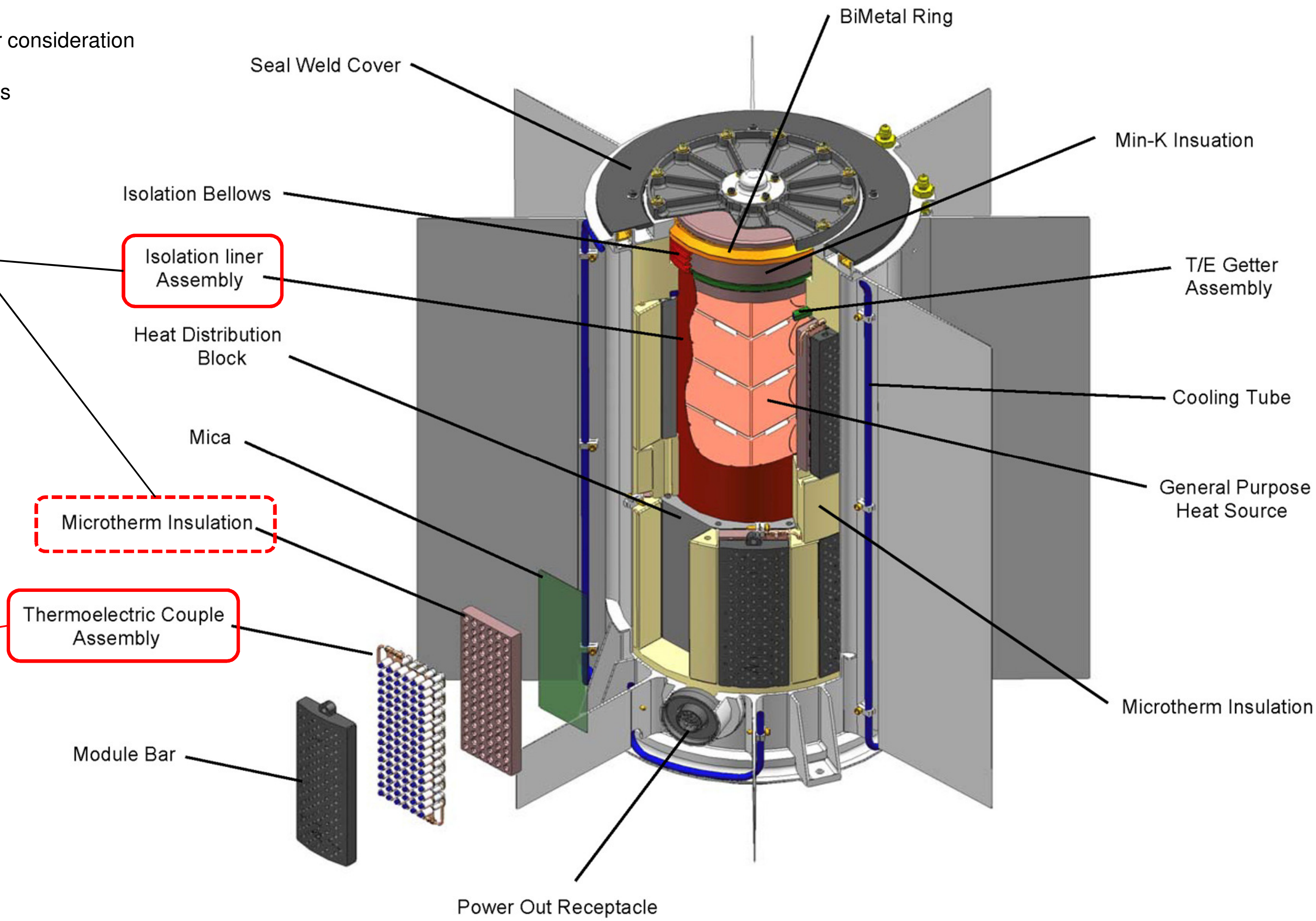
Enhancements under consideration

Known enhancements

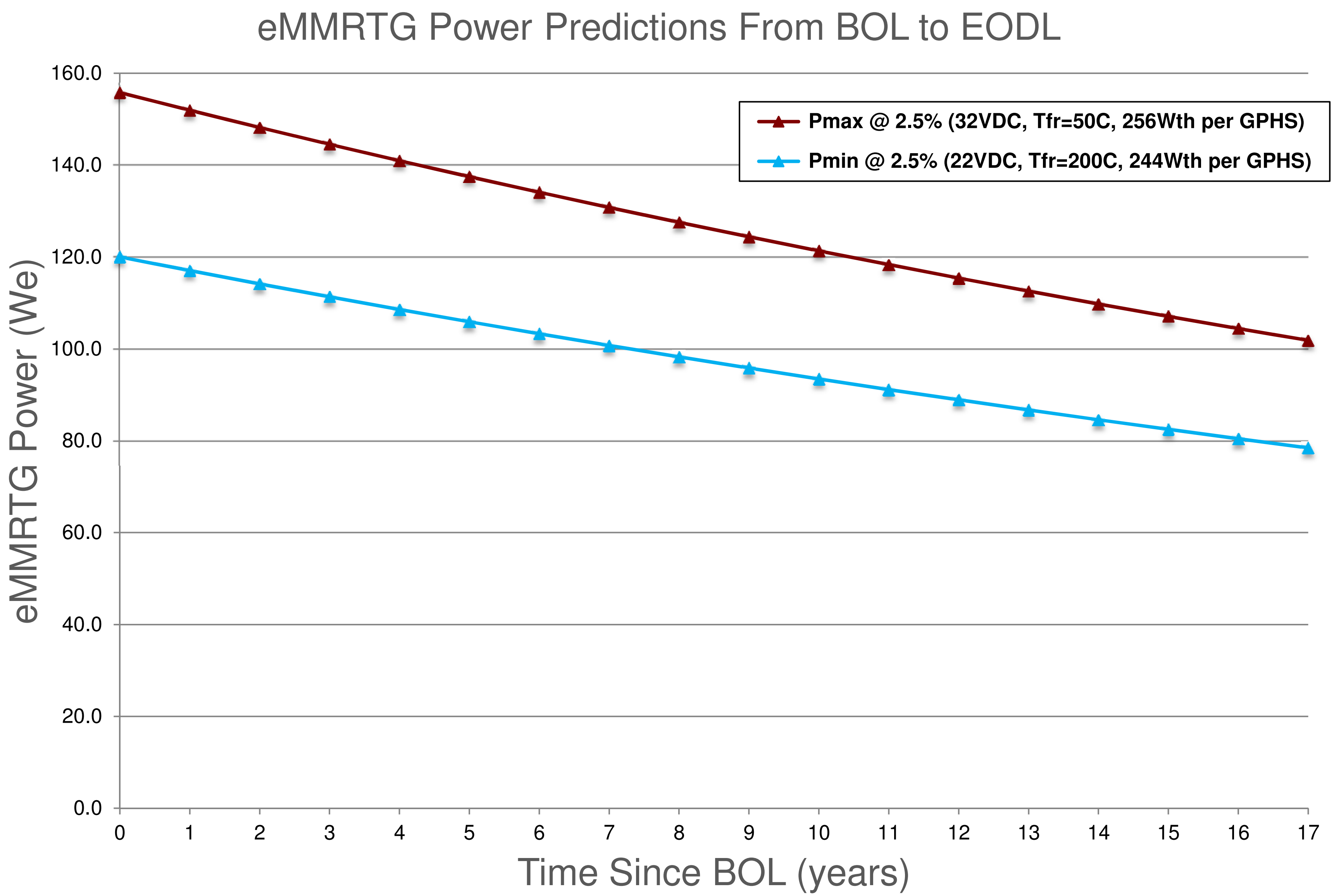
Engineering: emissivity change to liner, substitute insulation

Changes needed to MMRTG

New Technology: Substitute SKD thermoelectric couples



Max/Min Power Envelope



Informational, actual power figures may vary

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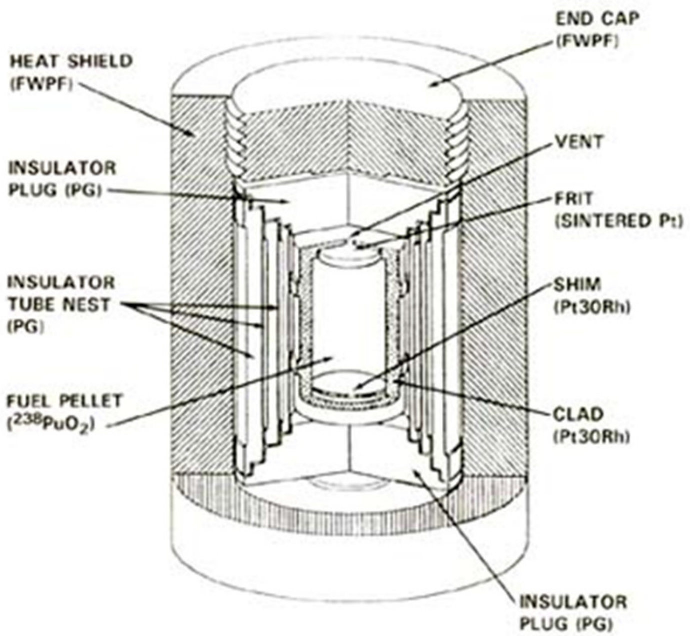
RHU Characteristics

Characteristics of RHUs include:

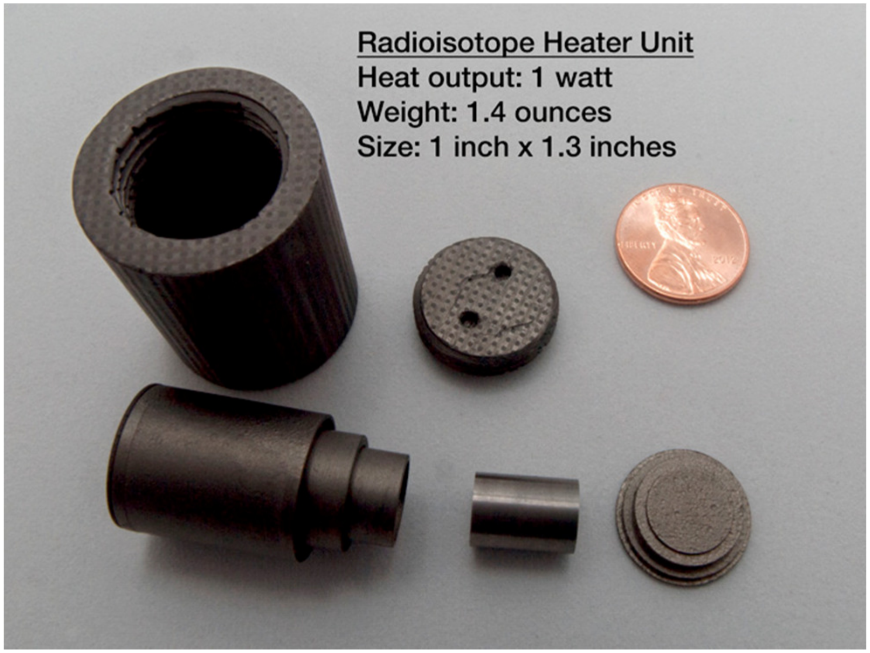
- *Highly reliable, continuous, and predictable heat output*
- *Simple, No moving parts*
- *Compact structure*
- *Resistant to radiation and meteorite damage*
- *Heat produced is independent of distance from the sun*
- *Heat is transferred through direct contact with components*
- *Extremely rugged and safe*



- 1.3 inches long and 1 inch in diameter
  (the fuel pellet is about the size and shape of a pencil eraser)
- Approximately 2.7 grams of plutonium dioxide
  (2 grams of Pu-238)
- Total weight of the RHU is approximately 40 grams
  (1.4 ounces)
- RHUs can be used singly or in groups
- Installed via a bolt-on fixture

RHU Characteristics

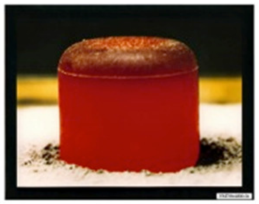
- RHUs are small devices that provide heat through radioactive decay of a small pellet of plutonium dioxide (comprised mostly of plutonium-238).
- Provides highly localized heating of sensitive equipment (such as electronics) in deep space where insolation is an insufficient source of heat.
- Transfers heat to spacecraft structures, systems and instruments directly without moving parts or intervening electronic components
- Cost $0.150M



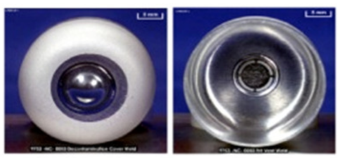
Benefits:
- Eliminates electric heaters
- More electric power for spacecraft, science
- Reduced complexity
- Less potential EMI
- Reliable, consistent thermal power for decades

RPS Considerations:
RPS PRODUCTION STEPS

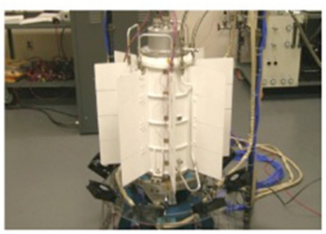
Plutonium Oxide (PuO_2) Fuel Pellet Production
LANL



Iridium Component Fabrication
ORNL



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

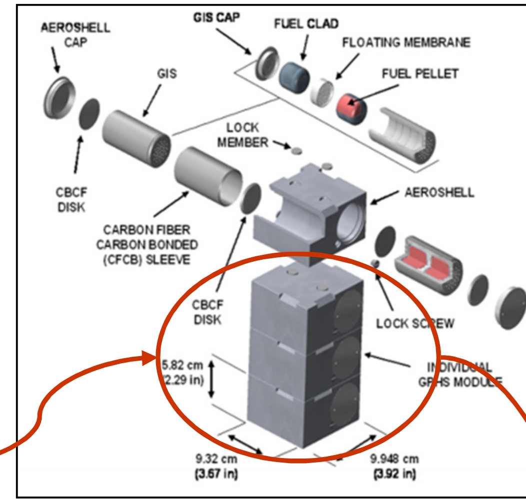


Fuel Pellet Encapsulation
LANL

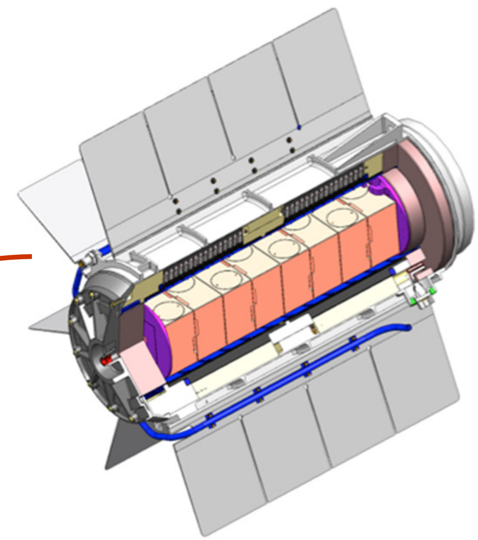
General Purpose Heat Source Module Assembly
INL

RPS Assembly and Testing
INL

RPS Shipment to KSC
INL



General Purpose Heat Source Module



RPS Considerations:
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

Ground Operations Planning

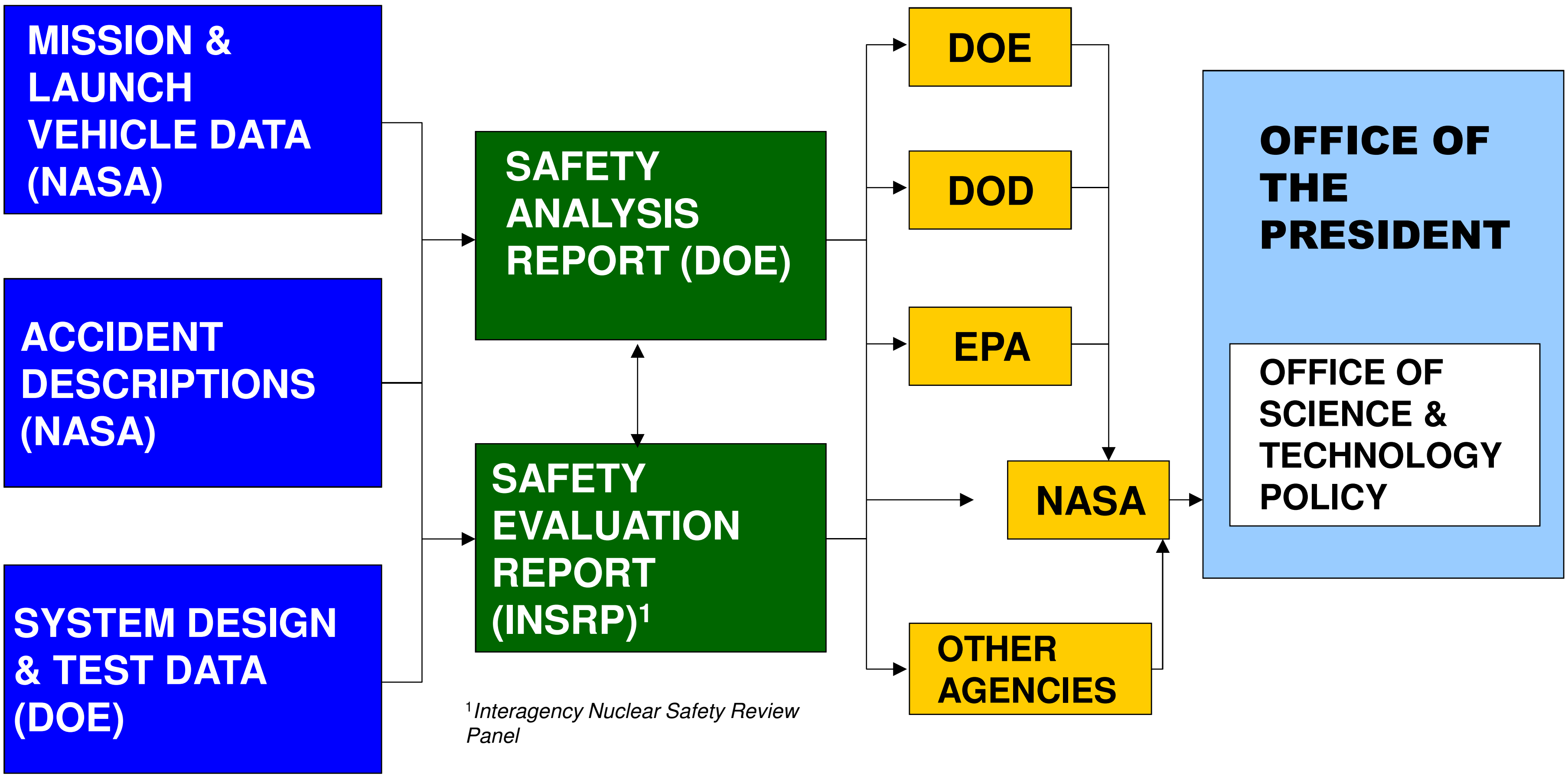
- DOE supports; NASA/KSC and the mission lead
- Major elements:
  - Planning for getting generators to KSC, unloading, monitoring and maintenance INL conducts in RTGF
  - Support to mission ATLO process

  - Develop procedures to be used for handling at KSC
  - Conduct trailblazer (takes a mockup RPS through process of moving to VIF, lift, SC integration)

RPS Considerations:
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

RPS Considerations:
NUCLEAR SAFETY REVIEW AND LAUNCH APPROVAL PROCESS

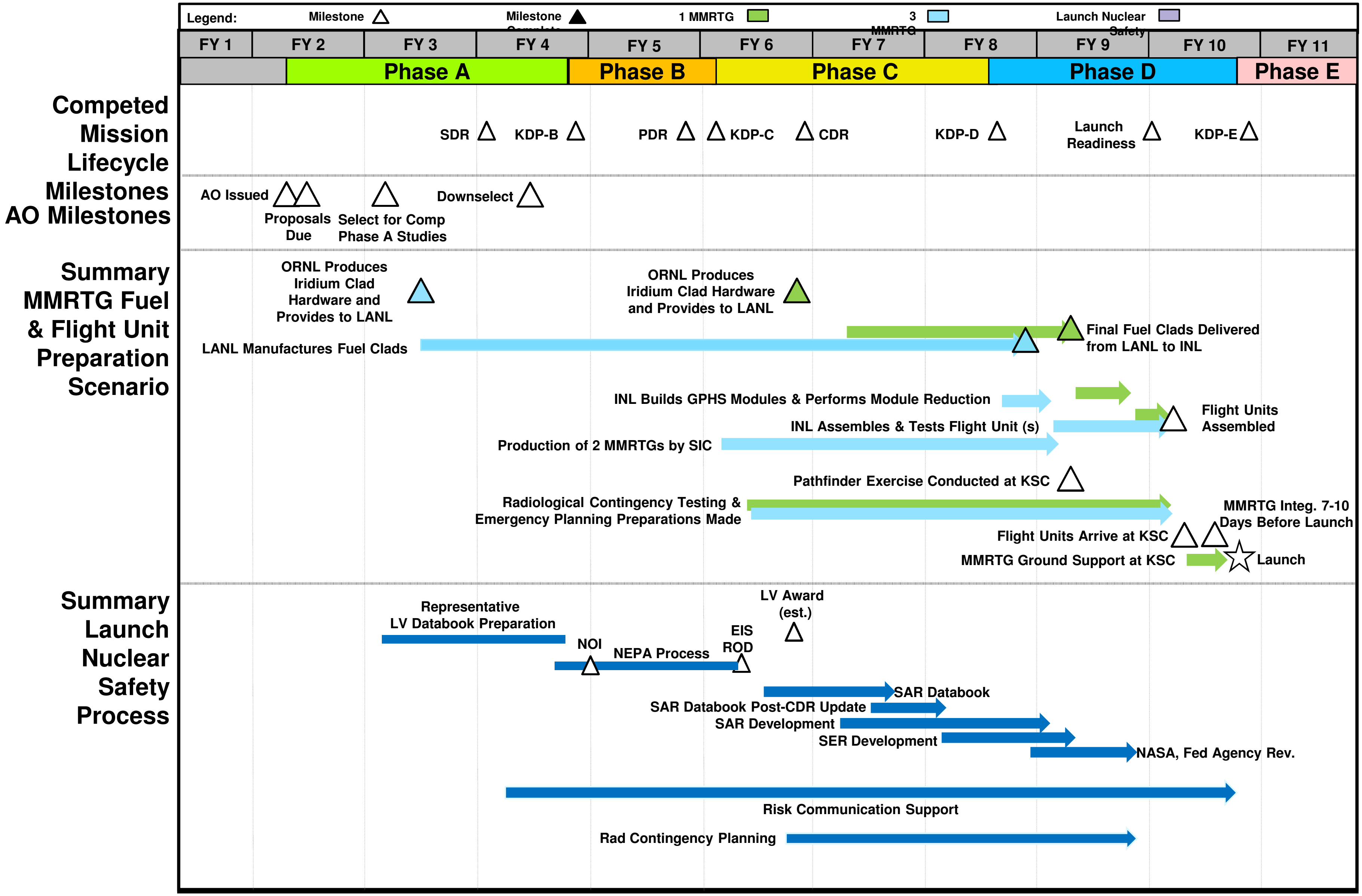


[1] *Interagency Nuclear Safety Review Panel*

DOE prepares a nuclear risk assessment which will be used by the Office of President to make a decision to authorize a launch using nuclear materials.

RPS Considerations:

Significant MMRTG–Related Mission Development Milestones



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HOW TO GET ADDITIONAL INFORMATION

MMRTG Mission Planner Data Package Summary

- **U.S. Citizens** may request approval to access the Data Package
- Data package includes:
  - MMRTG User's Guide
  - Test Reports (select)
  - Models: thermal and dynamic analytical, and CAD of exterior
- *Only* ***<u>one individual per organization</u>*** *will be granted access to the repository*.
  - The definition of "organization" is subject to the discretion of the RPS Program and DOE
  - Applicants will become that company's Point of Contact for any future applicants

MMRTG User's Guide – MMRTG Technical Data Source
Will be Available in the MMRTG Mission Planner Data Package 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
- Summary of Available Analytical and CAD Models

Access Request

- Download 1) Data Package *Request* and 2) *Usage Agreement* from **http://rps.nasa.gov/datapackage/**
- Submit completed and signed forms via email to: rps@nasa.gov
  - Use **Subject line labeled: MMRTG Mission Planner Data Package Request**
- **Please provide as attachments to email:**
  1. MMRTG Mission Planner Data Package *Request*
     - Includes professional contact info and "Intended Use Statement"
  2. MMRTG Mission Planner Data Package *Usage Agreement*
- RPS Program will review applications within 10 business days
- Shipment of data package may take 3 – 5 days

Questions?

rps@nasa.gov

RPS
Radioisotope
Power Systems

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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.