LPSC Community Dialogue:
Usage of Multi-Mission Radioisotope Thermoelectric Generators (MMRTGs) for Future Potential Missions

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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
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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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.

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
Public Domain Reference:
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

<table>
<thead>
<tr>
<th>Item</th>
<th>Multi-mission</th>
<th>MSL</th>
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<tr>
<td><strong>Performance</strong></td>
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<tr>
<td>Thermal Inventory</td>
<td>244-256 W/GPHS</td>
<td>244-256 W/GPHS</td>
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<tr>
<td>BOM power at 28 V</td>
<td>&gt; 110 W</td>
<td>&gt; 110 W</td>
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<td>Load voltage range</td>
<td>22-36 Vdc</td>
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<tr>
<td>Mass</td>
<td>&lt;45 kg</td>
<td>&lt;46.5 kg</td>
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<td>0.03 g2/Hz</td>
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<td>0.06 g2/Hz</td>
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<td>6000 g</td>
<td>3000 g</td>
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<td><strong>Environment</strong></td>
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<tr>
<td>Fin root temperature range</td>
<td>50°C to 200°C</td>
<td>50°C to 200°C</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>vacuum &amp; atm</td>
<td>vacuum &amp; atm</td>
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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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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.
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.
Max/ Min Power Envelope

MMRTG Power Predictions From BOL to EODL

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 Production Steps

1. Plutonium Oxide (PuO₂) Fuel Pellet Production
   LANL

2. Fuel Pellet Encapsulation
   LANL

3. General Purpose Heat Source Module Assembly
   INL

4. RPS Assembly and Testing
   INL

5. RPS Shipment to KSC
   INL

General Purpose Heat Source Module

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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
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
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 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
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
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)
Significant MMRTG-Related Mission Development Milestones

**Legend:**
- Milestone
- Milestone Complete
- 1 MMRTG
- 3 MMRTG
- Launch Nuclear Safety

<table>
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<tr>
<th>FY 1</th>
<th>FY 2</th>
<th>FY 3</th>
<th>FY 4</th>
<th>FY 5</th>
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<td><strong>Phase A</strong></td>
<td><strong>Phase B</strong></td>
<td><strong>Phase C</strong></td>
<td><strong>Phase D</strong></td>
<td><strong>Phase E</strong></td>
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<td>KDP-B</td>
<td>PDR</td>
<td>KDP-C</td>
<td>CDR</td>
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<td>Launch Readiness</td>
<td>KDP-E</td>
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**AO Milestones**
- AO Issued
- Proposals Due
- Downselect

**Summary**

- **MMRTG Fuel & Flight Unit Preparation Scenario**
  - ORNL Produces Iridium Clad Hardware and Provides to LANL
  - LANL Manufactures Fuel Clads
  - INL Builds GPHS Modules & Performs Module Reduction
  - INL Assembles & Tests Flight Unit(s)
  - Production of 2 MMRTGs by SIC
  - Radiological Contingency Testing & Emergency Planning Preparations Made
  - Pathfinder Exercise Conducted at KSC
  - Flight Units Arrive at KSC
  - MMRTG Integ. 7-10 Days Before Launch
  - Final Fuel Clads Delivered from LANL to INL

**Summary**

- **Launch Nuclear Safety Process**
  - Representative LV Databook Preparation
  - NEPA Process
  - NOI
  - EIS ROD
  - SAR Databook
  - SAR Databook Post-CDR Update
  - SAR Development
  - SER Development
  - LV Award (est.)
  - Risk Communication Support
  - Rad Contingency Planning

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## RPS Cost for
### Projected 2025 Mission

<table>
<thead>
<tr>
<th>RPS Type and Quantity</th>
<th>Cost to Fuel &amp; Launch System ($M)</th>
<th>Additional Cost for LSP ($M)</th>
<th>Additional Cost ($M)</th>
<th>Total ($M)</th>
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<td><strong>RPS &amp; RHU Missions</strong></td>
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<tr>
<td>1 MMRTG</td>
<td>105</td>
<td>28</td>
<td>0</td>
<td>133</td>
</tr>
<tr>
<td>2 MMRTG</td>
<td>135</td>
<td>28</td>
<td>0</td>
<td>163</td>
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<tr>
<td>3 MMRTG</td>
<td>165</td>
<td>28</td>
<td>0</td>
<td>193</td>
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<tr>
<td>1 MMRTG + RHU (Quantity &lt; 43)¹</td>
<td>105</td>
<td>28</td>
<td>2²</td>
<td>135</td>
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<tr>
<td>2 MMRTG + RHU (Quantity &lt; 43) ¹</td>
<td>135</td>
<td>28</td>
<td>2²</td>
<td>165</td>
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<tr>
<td>3 MMRTG + RHU (Quantity &lt; 43) ¹</td>
<td>165</td>
<td>28</td>
<td>2²</td>
<td>195</td>
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<tr>
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<td>105</td>
<td>28</td>
<td>34³</td>
<td>167</td>
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<tr>
<td>2 MMRTG + RHU (Quantity = 150)</td>
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<td>28</td>
<td>34³</td>
<td>197</td>
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<tr>
<td>3 MMRTG + RHU (Quantity = 150)</td>
<td>165</td>
<td>28</td>
<td>34³</td>
<td>227</td>
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<td>Quantity &lt; 43</td>
<td>24</td>
<td>21</td>
<td>2</td>
<td>47</td>
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<tr>
<td>Quantity &gt;43 and &lt; 190</td>
<td>24</td>
<td>21</td>
<td>34³</td>
<td>79</td>
</tr>
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</table>

1. Currently, 43 units are available. All are near 0.89 W<sub>th</sub>
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.
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 NpO₂ from INL to ORNL has occurred in November
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%)

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Potential for Higher Efficiency Systems

MMRTG and Proposed eMMRTG, Fueling thermal inventory

= $244W_{th},$

Space Environment = 4K sink

A Specific Case
How to Get Additional Information

RPS User’s Library Summary

• A RPS User’s Library is being developed
• 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