A Comparison of Radioisotope and Solar Array/Battery Power Systems in the Solar System
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Overview

- Radioisotope Power Systems (RPS) are an enabling technology for missions where solar array/battery systems are impractical
  - Low solar intensity
  - Long duration of darkness
  - Waste heat to keep spacecraft warm
- Request from Radioisotope Program Office for recreation of figure comparing RPS and solar power systems
- Figure (top) shows the mass required to provide a continuous 100 watts at various orbital locations in the solar system
  - Assumes
    - Array always faces sun
    - No periods of darkness and therefore no energy storage
    - Excluded planetary body surface operations
      - No atmosphere
  - Incomplete picture of RPS utility so additional variables added
    - Surface operation and energy storage
Radioisotope Power Systems

- **Multi-Mission Radioisotope Thermoelectric Generator** is the only available generator from DOE
  - Capable of operating in gaseous or vacuum environments with atmosphere (i.e. earth ground operations, Mars, Titan)

- **NextGen RTG**
  - Three Versions consideration
    - NextGen RTG Mod 0
      - Use of spare parts from GPHS RTG + possible accommodation of Step 2 GPHS modules
    - NextGen RTG Mod 1
      - GPHS RTG recreation to the extent possible with accommodation for larger GPHS (Step 2)
    - NextGen RTG Mod 2
      - New, higher performance thermoelectrics

- Vacuum only operation

- **Dynamic Radioisotope Power System (DRPS)**
  - Stirling Convertors
  - High efficiency reduces isotope consumption
  - Multi mission capability
## Performance of RPS

<table>
<thead>
<tr>
<th></th>
<th>MMRTG</th>
<th>NextGen RTG Mod-1 Projected Performance</th>
<th>DRPS - Projected Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>#GPHS</strong></td>
<td>8</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td><strong>Converter</strong></td>
<td>PbTe</td>
<td>SiGe</td>
<td>Stirling</td>
</tr>
<tr>
<td><strong>BOL power output, watts</strong></td>
<td>124</td>
<td>245</td>
<td>351</td>
</tr>
<tr>
<td><strong>EODL power output, 17 yr, watts</strong></td>
<td>70</td>
<td>177</td>
<td>283</td>
</tr>
<tr>
<td><strong>BOL efficiency</strong></td>
<td>6.2%</td>
<td>6.1%</td>
<td>23.4%</td>
</tr>
<tr>
<td><strong>Degradation Rate (DR) (%/yr) Avg over 17 years (expt-DR*time)</strong></td>
<td>3.8%/y</td>
<td>1.9%/y</td>
<td>1.2%/y</td>
</tr>
<tr>
<td><strong>BOL specific power, W/kg</strong></td>
<td>2.7</td>
<td>4.4</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Waste Heat, watts</strong></td>
<td>1876</td>
<td>3755</td>
<td>1149</td>
</tr>
<tr>
<td><strong>Relative Micrometeoroid and Orbital Debris Tolerance (MMOD)</strong></td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
</tr>
</tbody>
</table>

**Color Legend**
- Green – Available
- Yellow – Small Deviation from GPHS RTG, high confidence in performance projections
- Orange – New Power Convertors and Generator Design, some uncertainty in generator and convertor performance
RPS in the Inner Solar System

- Two environments critical for Radioisotope Power Systems
  - Thermal
  - Chemical
- Mercury
  - Operation not possible during daylight for any of the RPS (400 C surface)
  - Operation in permanently shadowed regions or during 1408 hours of darkness should be possible and the performance should be close to that in deep space
- Venus
  - 500 C surface temperatures and 95 Bars CO₂ precludes operation on surface for any of the RPS considered
    - Some preliminary design efforts to make a RPS system capable of surface operation have been explored but these designs are not extensible to other locations
  - MMRTG or DRPS may be able to operate in the upper atmosphere but may require mission accommodation
RPS for Lunar and Mars Operation

• **MMRTG**
  - **Lunar**
    - Not designed for lunar operation and may need modification when operating near equator
    - Lower initial heat inventory
    - Protection of TE modules from MMOD
    - White paint used to reduce solar input effectiveness may be reduced due to dust accumulation
  - **Mars**
    - Small reductions in power output due to atmosphere thermal environment (Curiosity MMRTG power output ranged from 109 to 119 during a Mars sol)
    - Generator appears to self cleans via convection

• **NextGen-Mod-0 through Mod-2**
  - **Lunar**
    - Similar accommodations to MMRTG may be required at/near equator
  - **Mars**
    - Atmosphere precludes NextGen series from operation on Mars
      - Atmosphere would interact with both GPHS modules, thermoelectrics and other components

• **DRPS**
  - **Lunar**
    - Power Variations during lunar day/night cycle and location dependent
    - Current DRPS requirements should allow operation at the equator
  - **Mars**
    - Small power variation during Mars day/night and location dependent

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Lunar Equatorial Power output of a 6 GPHS 8 Convertor DRPS with dust covering heat rejection surfaces
Other Bodies

• All the RPSs considered should be able to operate for either flyby or orbital missions from Mars out to Pluto and beyond at near deep space power output.

• For landers there are 7 moons have very thin atmosphere and MMRTG and DRPS should provide power output similar to deep space operation (Ganymede, Europa, Callisto, Rhea, Dione, Enceladus, and Titania).

• NextGen RTG may have difficulties on Triton and Io’s with its thicker atmosphere (component atmospheric interaction, MLI thermal conductivity).

• NextGen RTG operation on Icy world surfaces is still unknown even with very low-pressure atmospheres.
  • “It would generally seem that the physical process of water sublimation and diffusion into an RTG would be unfavorable, but the potential consequence of water as a strong oxidizing agent getting into a vacuum rated RTG is significant enough that further studies would be required to understand and properly mitigate this risk.” Christofer Whiting, UDRI.
SOA Solar Array and Battery

- Solar Intensity falls as $1/\text{Distance}^2$
- Solar arrays are characterized by their areal power density (W/m²) and their Specific power (W/kg) at 1 AU and then adjusted for location
  - Values are based on Northrop Grumman’s Ultra Flex arrays on the Lucy Mission
- Mars operation was modeled for both Areocentric Longitude (i.e. time of year) and optical Depth
  - Optical depth values on Mars vary from about 0.4 for a clear day on Mars to 5.0 for a typical global dust storm.
    - Dust accumulation on arrays was not included
    - Largest recorded dust storm in 2018 had an optical depth $>9$ and caused Opportunity rover to stop working
- Titan
  - Atmospheric attenuation due to Titan’s thick atmosphere is a 10-fold reduction in solar intensity
  - Surface Solar Intensity is $\sim1.5$ W/m²

### Lithium-Ion Battery SOA

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<tbody>
<tr>
<td>Specific energy, W-h/kg</td>
<td>175</td>
<td></td>
</tr>
<tr>
<td>Gravimetric energy density, W-h/liter</td>
<td>194</td>
<td></td>
</tr>
<tr>
<td>Depth-of-discharge, %</td>
<td>80</td>
<td></td>
</tr>
<tr>
<td>Charge/discharge efficiency, %</td>
<td>90</td>
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### Fold Out Flexible Array

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<tbody>
<tr>
<td>Conversion efficiency, %</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Areal power density at 1 AU, W/m²</td>
<td>415</td>
<td></td>
</tr>
<tr>
<td>Specific power at 1 AU, W/kg</td>
<td>184</td>
<td></td>
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</tbody>
</table>

### Table 3. Battery Performance

![Graph showing peak solar flux and areocentric longitude with optical depth values]
Solar Array/Battery systems operation throughout solar system

- Day/Night cycles were set by assuming equatorial landing
- Most moons of the solar system are tidally locked, so the bodies day equals the orbital solar period.
  - Uranus is unusual in that its axial tilt is so high that on its satellites the sun will rise and set only once per Uranus year unless the surface location is within about 8° of the equator.
  - Pluto similarly has such a high axial tilt to the plane of its orbit that any surface object more than 33° is in the polar regions.
- Following figures are for equatorial operation and show best case solar array and battery mass where day/night cycles are equal
  - Excluding polar regions which may have continuous illumination
Sidereal Period

- Earth-orbit
- Earth surface
- Moon
- Mars-orbit
- Mars Surface-Clear
- Mars Surface-Dust Storm-OD 1
- Mars Surface-Dust Storm-OD 5
- Delmos
- Jupiter-Orbit
- Io
- Europa
- Ganymede
- Callisto
- Saturn
- METDrhp-avg
- Titan
- Iapetus
- Uranus-Orbit
- MAUTO-avg
- Neptune-Orbit
- Proteus, Triton (avg)
- Pluto-Orbit

Sidereal Period (earth days)
Providing 100 watts Continuous at Various Locations in the Solar System

- Solar Array: Eff = 32%, 2.25 kg/m²
- Battery: 194 Wh/kg, 80% DoD, CDC Eff = 90%
- Assume tracking array-no mass, equatorial location
- MMRTG 2.5 W/kg, DRPS 3.7 W/kg, NextGen RTG Mod1-4.1
- Atmospheric attenuation for Mars and Titan only
- METRHP-Mimas, Enceladus, Tethys, Dione, Rhea, Hyperion, Phoebe=0.4-4.5-day period
- MAUTO-Miranda, Ariel, Umbriel, Titania, Oberon - 1.41- to 13.48-day period
- Does not include battery heaters/RHUs and associated power consumption
Conclusions

• Great progress has been made in both solar array and battery storage technologies, but nuclear systems are compelling and sometimes the only alternatives of power generation for many places in the solar system.

• MMRTG and DRPS Multi-Mission capability is an important feature for future exploration of icy world and other bodies.

• NextGen RTG Mod-1 should provide best specific power generator for vacuum only missions.

• Each RPS has their own compelling characteristics.
REFERENCES

  


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