Radioisotope-based Nuclear Power Strategy for Exploration Systems Development

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George Schmidt and Mike Houts
NASA Marshall Space Flight Center
U.S. Radioisotope Space Missions

RTGs used successfully on 23 spacecraft since 1961
- 8 Planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)
- 8 Earth Orbit (Transit, Nimbus, LES)
- 5 Lunar Surface (Apollo ALSEP)
- 2 Mars Surface (Viking)
Radioisotope Power Systems (RPS)

- Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)
  - 87.7-year half-life
- Small portion of heat energy (6%-25%) converted to electricity via passive or dynamic processes
  - Thermoelectric (existing & under development)
  - Stirling (under development)
  - Brayton, TPV, etc. (future candidates)
- Waste heat rejected through radiators – portion can be used for thermal control of spacecraft subsystems
Benefits of RPS

Provides the unique features of nuclear power sources, such as...

- Steady power delivery independent of distance and orientation with respect to sun;
- Operation in shadowed and heavily clouded regions and locations (craters, thick atmospheres);
- Power generation in extreme environments (Venus, Titan);
- Operation in high-radiation environments (Jovian space);
- Long duration operation (≥10 years);

Plus, the added advantages of...

- Scalability to very low power levels (≤1-10 kWe);
- Use in close proximity to crew (low penetrating radiation);
- Readily available excess heat;
- Compactness and ease of transport;
- Enables Radioisotope Electric Propulsion (REP) – benefits of NEP with low power spacecraft (1-5 kWe)
  - Application of high-performance electric propulsion in deep space
  - Specific powers comparable to near-term reactor-based NEP
  - Much smaller spacecraft
Recent and Planned RPS Units

SNAP-19
- Pb-Te/TAGS thermoelectrics
- 40.3 Watts (BOM)
- 6.2 % eff; 3 We/kg
- Nimbus B-1/III
- Pioneer 10 & 11
- Viking 1 & 2

Multi-Mission RTG (MMRTG)
- Mars Science Lab (MSL)
- Other missions

1990
- GPHS RTG
  - Si-Ge thermoelectrics
  - 42.7 dia x 44.9 long (cm)
  - 292 We (BOM)
  - 6.8% eff; 5.2 We/kg
  - Galileo
  - Ulysses
  - Cassini
  - Pluto New Horizons (New Frontiers 1)

1980
- Multi-Hundred Watt (MHW) RTG
  - Si-Ge thermoelectrics
  - 39.7 dia x 58.4 long (cm)
  - 158 We (BOM)
  - 6.6 % eff; 4.2 We/kg
  - LES 8 & 9
  - Voyager 1 & 2

1970
- SNAP-19

Stirling Radioisotope Generator (SRG)
- 40.3 Watts (BOM)
- 6.2 % eff; 3 We/kg
- Nimbus B-1/III
- Pioneer 10 & 11
- Viking 1 & 2

1980
- Multi-Mission RTG (MMRTG)

1990
- GPHS RTG

2000
- Multi-Hundred Watt (MHW) RTG

2010
- Stirling Radioisotope Generator (SRG)
Potential Future RPS-Powered Science Missions

**Under Current Study**
- **Planetary Atmospheric Missions:** 100W-class units, ≥14 yr lifetime, ops in Mars & Titan environment
  - Mars Science Lab (2009): ~100W
  - Mars Astrobiology Field Lab (2016-18): ~100W
  - Titan Explorer/Aerobot (2020-25): ~100W
- **Deep Space Missions:** 100W-class units, ≥14 yr lifetime
  - Solar Probe (2015): ~300W
  - Europa Geophysical Explorer (2016): ~800W
  - Titan Explorer/Orbiter (2020-25): 100’s of watts
- **Venus Surface Explorer (2020-25):** 100’s of watts, ≤3 yr lifetime, integrated Stirling cooler/power generator

**Not Under Serious Consideration at Present**
- **Small Surface Missions:** 10W-class units, ≥14 yr lifetime
  - Mars Netlander (≥2020): 10’s of watts
  - Fetch Rovers (≥2020): 10’s of watts
- **REP-based Deep Space Missions:** 100W-1kW units, ≥14 yr lifetime, ≥8 We/kg
  - New Frontiers missions (≥2020): ≤1 kW (e.g., Trojans, Centaurs)
  - Flagship missions (≥2025): 3-4 kW (e.g., Neptune/Triton, Interstellar Probe)
- **REP-based Missions to Giant Planets (≥2030):** 1kW units, ≥14 yr lifetime, ≥10 We/kg
  - Jovian System Tour (JIMO Lite) (≥2030): ≤5 kW
  - Tours of Other Outer Planetary Systems (≥2030): ≤5 kW
Potential Lunar and Mars Surface Exploration Applications

- Robotic Rovers: 100W-class units, ≥2 yr lifetime, ops in sunlit and shadowed areas on moon
  - RLEP-2 (2011): ~100 W
- Milliwatt-scale units for transponder and beacon applications (≥2011): 10-100 mW
- 100W-scale Portable Generator: Transported to moon on crewed sorties. No more than 2 sorties per year. Accumulate at site for future use.
  - Sortie mission deployable science packages (2018-2025): 4 types defined ranging from 50 W to 500 W
  - Extended mission deployable science packages (≥2025): 3 types defined ranging from 100 to 500 W
- 1kW-scale Portable Generator: Transported to moon on crewed sorties. No more than 2 sorties per year. Accumulate at site for future use.
  - Sortie habitat power for stays ≥14 days (≥2020): 4 kW
  - Emergency power ≥14 days (≥2020): 1-3 kW
  - Lunar pressurized rover (≥2025): 7 kW
  - Extended mission deployable 10-meter drill (≥2025): 6 kW
  - Communication/navigation station (≥2025): 1 kW
Cross-Cutting Applications for Small and Large RPS

Small RPS (mWe to several We)
- Numerous potential planetary surface and space applications (e.g., networked science stations, deployable mini-payloads)
- 3 general size ranges using existing Pu-238 thermal sources
  - 40-80 mW (based on 1-few RHUs)
  - 0.1-few W (based on multiple RHUs or fractional GPHS)
  - 10-20 W (based on single GPHS module)

Radioisotope Electric Propulsion (REP)
- Low power NEP concept based on RPS as principal power source
- Science application for large RPS (≥1 kWe)
- Enables use of high-performance electric propulsion independent of distance from Sun (i.e., deep space)
- Compatibility on small spacecraft permits launch system injection into C3 > 0 and offsets performance disadvantage of low specific power
Plutonium-238 Requirements Versus Power Level

Efficiency (%)

Approximate Pu-238 Mass (kg)

Delivered Electric Power (kW)

GPHS RTG

Cassini Spacecraft

MMRTG

SRG

Evolution 2 (Upper Limit)

Evolution 3

Evolution 2 RPS

Efficiency (%)

5

10

15

25

35

Reactor Spacecraft

Upper Limit (Evolution 2 RPS)
Possible Scenario for Nuclear Power Evolution

- **Exploration Applications**
  - Lunar rovers
  - Autonomous stations

- **Science Mission Applications**
  - MSL
  - Europa Geo Orbiter
  - Solar Probe

- **Current/Near-Term RPS**
  - REP
  - More capable science missions

- **2nd Gen RPS**
  - Crew power & heat
  - Crew rovers

- **Realistic 1st Gen FPS***
  - Base operations

- **Poor Man’s NEP**
  - Large science stations/payloads

* Fission Power System (FPS)
Possible Scenario for Nuclear Power Evolution

**Existing Capability**
GPHS RTG

**Phase 1**
Stirling Radioisotope Generator (SRG) and Multi-Mission RTG (MMRTG)
- MMRTG

**Phase 2**
High-Performance/High-Power RPS Generator
- Stirling-based concept

**Phase 3**
Multi-Kilowatt Source (Reactor or RPS)
- Reactor concept

**Potential Mission Applications**
- Rovers and landers for robotic lunar science missions
- Deployable instrument packages and stations
- Robotic planetary missions

**Current nuclear power source in U.S. inventory**
- 285-300 We at BOM
- 5.2 We/kg specific power

**Currently under development by RPS program**
- 110-125 We at BOM
- ~3 We/kg specific power

**Based on advances from current technology projects**
- Up to 1-2 kWe
- 8-10 We/kg

**Based on converters from Spiral 2 RPS unit**
- 10-40 kWe
- 10-12 We/kg

**Potential Mission Applications**
- Large scale support operations for crewed missions (rovers, instrument packages, base power)
- Electric propulsion for 3-4 kW robotic probes
- Centralized power source for extended crew operations on Moon and Mars
- Power source for crewed spacecraft
Backup
Progression in Capability

Lunar Robotic Science
- High-Performance Stirling Technology (Developed under RPCT, SBIR & GRC research)

Short Crewed Missions
- SRG
  - 112 We
  - 24% efficiency
  - 3.3 We/kg sp power
- kW-Class Stirling
  - 1-2 kWe
  - 30-35% efficiency
  - 8-10 We/kg sp power

Extended Crewed Missions
- Multi-10 kW Power System
  - 20-30 kWe
  - 30-35% efficiency
  - 10-14 We/kg sp power

Power Conversion

Heat Source

Reactor Technology (Developed under Prometheus)

DRAFT - pre-decisional for information purposes only