NASA Missions Enabled by Space Nuclear Systems

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Space Nuclear System Applications

Electric Power Generation

Thermal Propulsion
Commercial/Military Electric Power Systems:

- Development, Production & Operation Cost ($/kW)
- Specific Power/Energy (kW/kg, kWh/kg)
- Emissions ($NO_x$, $CO_x$, noise)

PUBLIC SAFETY
Spacecraft Power Systems:

- Specific Energy (kWh/kg)
- Specific Energy (kWh/kg)
- Specific Energy (kWh/kg)
- Development Cost
Power Generation Specific Energy Trade Space

- **Primary Batteries**
- **Fuel Cells**
- **Solar Arrays**
- **Radioisotopic Thermal Generators**
- **Nuclear Reactors**

**Use Duration**
- 1 Minute
- 1 Hour
- 1 Day
- 1 Month
- 1 Year
- 7 - 10+ Years

**Electric Power (Watts)**
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$
- $10^7$

**Power Generation Specific Energy Trade Space**

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Pu-238

Radioisotope Power Generation

- Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)
  - 87.7-year half-life
- Waste heat rejected through radiators – or can be utilized for thermal control of spacecraft subsystems

Pu-238 → U-234

\[ \alpha \text{(He-4)} \]

\[ 5.6 \text{ MeV} \]

Source: NASA HQ/L. Dudzinski

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Radioisotope Power Generation

- Steady power independent of distance and orientation w/respect to Sun;
- Operation in thick atmospheres and shadowed areas;
- Operation in extreme and high-radiation environments (e.g., Venus, Titan, Jovian space);
- Long duration operation (≥10 years);
- 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)
  - High-performance electric propulsion in deep space
  - Specific powers comparable to near-term reactor-based NEP
  - Much smaller spacecraft
- RTG’s were used safely in 26 missions since 1961
  - 10 Earth orbit (Transit, Nimbus, LES)
  - 8 planetary (Pioneer, Voyager, Galileo, Ulysses, Cassini, New Horizons)
  - 6 on lunar surface (Apollo ALSEP)
  - 2 on Mars surface (Viking I & 2)
- 3 RHUs on Mars Pathfinder, 8 RHUs for each MER

Source: NASA HQ/L. Dudzinski
Distances & Planets Are Not To Scale
Radioisotope Power Generation

Plutonium Supply Limitations

- Potential mission roadmap demand exceeds available Pu\textsuperscript{238} & new Pu\textsuperscript{238} production rate
- Mission planning will have to reconcile with actual Pu\textsuperscript{238} availability

Pu\textsuperscript{238} Supply

Remaining Russian Pu\textsuperscript{238} Purchases

Potentially Available New Pu\textsuperscript{238} Production

Pu\textsuperscript{238} Outflows


Year

Source: NASA HQ/L. Dudzinski

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Radioisotope Thermoelectric Generation (RTG)
- Decay heat to DC electricity via thermoelectrics
- <8% conversion efficiency
- Specific power ~3 W/kg
- Long history in unmanned deep space probes

Advanced Stirling Radioisotope Generator
- Decay heat to AC electricity via stirling conversion
- >30% conversion efficiency
- Specific power ~7 W/kg
- Next generation technology
Fission Power Generation

SNAP-10
- Launched 1965
- ~500 We
- Thermoelectric

SP-100
- Designed 1990’s
- 100 kWe
- Thermoelectric
- Fast spectrum
- Li coolant
- T = 1375K
- Nb-Zr cladding

JIMO
- Designed 2000’s
- 200 kWe
- Brayton
- Fast spectrum
- HeXe coolant
- T = 1050K
- Refractory cladding

Fission Surface Power
- Current study group
- 25-100 kWe
- Brayton or stirling
- Fast spectrum
- NaK coolant
- T = 900K
- Stainless steel cladding

U-235 Neutron Capture Spectrum
Solar Powered Lunar Outpost

Scenario 4.2.1

Source: NASA JSC/J. Poffenberger
Solar Powered Lunar Outpost

Static Polar Base with Excursions, LSS Scenario 4.3.1

- **Human Lunar Return**
  - Initial Core Capability

- **Start of Continuous Human Presence**

- **Missions of Opportunity**
  - (Repeat every year starting in FY2026)

**Notes:**
- 500 kg of payload (e.g., scientific research, commercial, Education and Public Outreach (EPO), International Partners, etc.) is delivered for each mission
  - 7 day missions have a rover and 250 kg of payload
  - Payload, unpressurized goods, liquids, and gases are not shown
  - Through FY31, there are:
    - 61 14-day and 132 3-day SPR excursions
    - 6,045 total hours of EVA at the Outpost
    - 14,964 total hours of EVA while on SPR Excursions

**Source:** NASA JSC/J. Poffenberger

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Solar Powered Lunar Outpost

Power System Concept

Stationary Outpost
• Ultraflex solar arrays
• Sizes from 5.5m diameter (Orion) up to 9.0m
• Power from 5.7 kWe to 15.9 kWe/array
• Regenerative fuel cells (gaseous reactant storage) or
• Advanced Li-ion secondary batteries for night energy storage

Mobility Applications
• SPRs traverse with logistics support vehicle equipped with a Mobility Power Unit (MPU)
• MPU is also equipped with solar arrays and Advanced Li-ion batteries
• SPRs periodically rejoin logistics vehicle to recharge
• Regenerative fuel cells will be needed on the logistics vehicle for long SPR traverses over the lunar night

Source: NASA JSC/J. Poffenberger

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Solar Powered Lunar Outpost

Solar Availability Model for Shackleton Rim Outpost

Source: NASA GRC/J. Fincannon
Solar Powered Lunar Outpost

Scenario 8.2.1

Extreme Mobility for Unlimited Exploration

Source: NASA JSC/J. Poffenberger
"Pervasive Mobility" Base Concept, LSS Scenario 8.2.1

Notes:
- 500 kg of payload (e.g., scientific research, commercial, Education and Public Outreach (EPO), International Partners, etc.) is delivered for each mission
- The 7 day missions have a rover and 250 kg of payload
- Payload, unpressurized goods, liquids, and gases are not shown
- Through FY30, there are 45 14-day and 107 3-day LER excursions

Source: NASA JSC/J. Poffenberger

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## Fission Powered Lunar Outpost

### Static Base with Excursions, LSS Scenario 5.6.2

<table>
<thead>
<tr>
<th>Human Lunar Return</th>
<th>Initial Core Capability</th>
<th>Start of Continuous Human Presence</th>
<th>Missions of Opportunity (Repeat every year starting in FY2026)</th>
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<td>Grew</td>
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<tr>
<td>CDK</td>
<td>AIA Adapter x2</td>
<td>Plant &amp; Tools</td>
<td>Durala</td>
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</table>

### Notes:
- 500 kg of payload (e.g., scientific research, commercial, Education and Public Outreach (EPO), International Partners, etc.) is delivered for each mission.
- The HLR mission has an Apollo Class Rover and 250 kg of payload.
- Payload, unpressurized goods, liquids, and gases are not shown.
- Through FY31, there are:
  - 62 14-day and 133 3-day SPR excursions
  - 5,723 total hours of EVA at the Outpost
  - 15,204 total hours of EVA while on SPR Excursions

### Table: Crew Size, Surface Duration, Mission Number

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<th>Year</th>
<th>Crew Size</th>
<th>Surface Duration</th>
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</table>

Source: NASA JSC/J. Poffenberger

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Fission Powered Lunar Outpost

Conceptual Fission Surface Power Emplacement Options

Source: NASA GRC/D. Palac
Fission Powered Lunar Outpost

“ROxygen” End to End $O_2$ Production from Lunar Regolith

Hydrogen Reduction Process

Regolith Inlet/Outlet Hopper & Auger Lift System

Two Fluidized $H_2$ Reduction Reactors - 10 kg/batch each

Water Electrolysis Module

Gaseous $O_2$ Storage

Cratos Excavator

Source: NASA JSC/T. Simon
Fission Electric Power Generation

Extensible to Mars

Design Reference Architecture 5.0
Surface Power System

• 30 kWe fission power system supports ISRU (prior to crew arrival) and during crew exploration
• Reactor deployed 1 km from lander remotely
• Close derivative of the lunar system

Source: NASA JSC/B. Drake
Fission Electric Power Generation

Extensible to Mars

Day Power (full array power of 5-PV/RFC Modules - only 3 kWe night power recharging)

If Solar

If Nuclear

Either

Source: NASA GRC/R. Cataldo

Legend

Rover Recharge
Logistics Module
Ascent Stage
ECLSS/EVA Cache

Deliver 5 - 5 kWe PV/RFC Modules
* Sufficient for O2 production when Habitat in standby Mode
* Not capable of dust storm crew survival
Fission Electric Power Generation

Extensible to Mars

![Graph showing power system mass for Solar / RFC and Fission Reactor](image)

- **Contingency**
- **Dust Storm Array Module**
- **Solar Module 5**
- **Solar Module 4**
- **Solar Module 3**
- **Solar Module 2**
- **Solar Module 1 or Reactor**

Source: NASA GRC/R. Cataldo
Fission Nuclear Thermal Propulsion
Key for Humans to Mars

Design Transition from Single Large NTR to Clustered Smaller Engines Supplying Modest Electrical Power

Reversible Lunar Transfer Vehicle using Single 75 klb Engine -- SEI (1990-91)

Expendable TLI Stage for First Lunar Outpost Mission using Clustered 25 klb Engines -- “Fast Track Study” (1992)

“Bimodal” NTR Earth Return Vehicle using Clustered 15 klb / 25 kW Engines -- Mars DRM 1.0 (1993)

Reusable Mars Transfer Vehicle using Single 75 klb Engine -- SEI (1990-91)

Artificial Gravity BNTR Crewed Transfer Vehicle also using Clustered 15 klb / 25 kW Engines -- Mars DRM 4.0 (1999)

Source: NASA GRC/S. Borowski
Fission Nuclear Thermal Propulsion
Key for Humans to Mars

Mars Design Reference Architecture 5.0 Mission Overview:
“7-Launch” NTR Option Shown

Source: Glenn Research Center

ISRU / propellant production for MAV
AC / EDL of MDAV / Cargo Lander
Habitat Lander AC into Mars Orbit
Cargo: ~350 days to Mars

4 Ares-V Cargo Launches
~26 months

Ares-I Crew Launch
3 Ares-V Cargo Launches
~30 months

~500 days on Mars

Crew: Use Orion/SM to transfer to Hab Lander; then EDL on Mars

Crew: Jettison drop tank after TMI; ~200 days out to Mars

Crew: Jettison DM & contingency consumables prior to TEI

Crew: ~200 days back to Earth

Orion direct Earth return

Ares-V Mars Requirements:

- ~140 t to LEO (407 km circ)
- ~10 m D x 30 m L
(Cylindrical PL Envelope)

Source: NASA GRC/S. Borowski

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“The first person to set foot on Mars is alive today in America”

- Boeing Outreach Poster