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)
Spacecraft Power Systems:

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

- **Fuel Cells**
- **Primary Batteries**
- **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)**
- $10^1$
- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$
- $10^7$

Pre-Decisional. For Discussion Only.

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Power Generation Specific Energy Trade Space

10^7
10^6
10^5
10^4
10^3
10^2
10^1
1 MINUTE
1 HOUR
1 DAY
1 MONTH
1 YEAR
7 – 10+ YEARS

ELECTRIC POWER (WATTS)

NUCLEAR REACTORS

FUEL CELLS

Shuttle

Gemini

Apollo CM/SM

Mercury

SOLAR ARRAYS

RADIOISOTOPIC THERMAL GENERATORS

ISS

JIMO

New Hori.

10^1
10^2
10^3
10^4
10^5
10^6
10^7
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

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

Source: NASA HQ/L. Dudzinski
- RTGs 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

**Radioisotope Missions**

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
- Existing Pu\textsuperscript{238} Inventory
- Current FWPF Limit
- Potentially Available New Pu\textsuperscript{238} Production

Pu\textsuperscript{238} Outflows

- Lunar Mission
- Exploration Rover Power
- Discovery 12
- MSI
- Discovery 15
- New Frontiers 4
- Exploration Rover Power
- Flagship 1
- Lander Power
- Lunar Rover
- Mars Mission


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

<table>
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<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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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
Solar Powered Lunar Outpost

Solar Availability Model for Shackleton Rim Outpost
Solar Powered Lunar Outpost

“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

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

- Launch 3 Missions per year. Series repeats as necessary to support sustained continuous human presence.

# Crew Size  # Surface Duration  Mission Number

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Source: NASA JSC/J. Poffenberger

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Fission Powered Lunar Outpost

Conceptual Fission Surface Power Emplacement Options

Source: NASA GRC/D. Palac
"ROxygen" End to End O₂ Production from Lunar Regolith
Hydrogen Reduction Process

Two Fluidized H₂ Reduction Reactors - 10 kg/batch each

Regolith Inlet/Outlet Hopper & Auger Lift System

Water Electrolysis Module

Gaseous O₂ 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)

---

100 90 80 70 60 50 40 30 20 10

kWe

If Solar  If Nuclear  Either

ECLSS/EVA/Ascent O2 Production (continuous operation)
ECLSS/EVA/Ascent O2 Production (operation 8 hr/day)
ECLSS/EVA Production Only
ECLSS/EVA Production Only

Pre-deploy Phase  Crew Phase

Rover Recharge  Logistics Module  Ascent Stage  ECLSS/EVA Cache

Legend

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

Source: NASA GRC/R. Cataldo

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Fission Electric Power Generation

Extensible to Mars

![Diagram showing power system mass breakdown for Solar/RFC and Fission Reactor]

Source: NASA GRC/R. Cataldo
Design Transition from Single Large NTR to Clustered Smaller Engines Supplying Modest Electrical Power

Reusable Lunar Transfer Vehicle using Single 75 klb₁ Engine -- SEI (1990-91)

Expendable TLI Stage for First Lunar Outpost Mission using Clustered 25 klb₁ Engines -- "Fast Track Study" (1992)

Reusable Mars Transfer Vehicle using Single 75 klb₁ Engine -- SEI (1990-91)

“Bimodal” NTR Earth Return Vehicle using Clustered 15 klb₁ / 25 kWₑ Engines -- Mars DRM 1.0 (1993)

Artificial Gravity BNTR Crewed Transfer Vehicle also using Clustered 15 klb₁ / 25 kWₑ 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

1. 4 Ares-V Cargo Launches
2. Cargo: ~350 days to Mars
3. Crew: Use Orion/SM to transfer to Hab Lander; then EDL on Mars
4. Ares-I Crew Launch
5. 3 Ares-V Cargo Launches
6. ~26 months

7. Ares-I Crew Launch
8. Crew: Jettison drop tank after TMI; ~200 days out to Mars

9. Crew: Jettison DM & contingency consumables prior to TEI
10. ~500 days on Mars
11. MAV ascent to orbit
12. Crew: ~200 days back to Earth
13. 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
“The first person to set foot on Mars is alive today in America”

- Boeing Outreach Poster