Surviving Night at the Lunar South Pole: Exploring Viability of Radioisotope Power Systems for a Crewed Rover

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Background

- In 2020, NASA put out a request for information regarding a Lunar Terrain Vehicle; a crewed rover supporting crew at the Lunar South Pole.
- We were asked to evaluate lunar night survival strategies for their benefits and drawbacks; one of these included radioactive power or thermal sources.
  - Answer the question "what are radioisotope power systems and how would they impact a rover design?"
  - Also answer "how can we tell a good design from a bad one?"
  - Similarly, have enough background to evaluate proposals from external vendors/startups that promise to deliver radioisotope systems with less red tape and more efficiency.

What will this presentation cover?

- Basics of radiation
- Flight heritage of radioisotope power systems
- Isotope downselection for radioisotope power systems
- Look at current and near-term solutions for spaceflight

What will this presentation *not* cover?

- How to shield radioactive systems for crewed use
- Convincing someone to give you the budget for radioisotope systems
- Detailed spacecraft design with RPS
- Who to contact if you are interested in utilizing radioisotope systems
    - NASA has a very helpful RPS office if you are interested in pursuing these systems in greater detail

The Lunar Night Survival Problem

- What's the big deal? Why look at RPS?
  - Surviving the lunar day alone: easy
  - Surviving the lunar night alone: easy
  - Surviving both? *Extremely challenging*
- Balance thermal needs:
  - Reject waste heat during the day
  - Maintain survival temperatures overnight… without depleting energy source
- Challenging environment
  - Approximately 4 weeks for one full day/night cycle
  - Extreme cold temperatures (as low as 25K) in permanently shadowed regions
  - It's the Moon, did we expect it to be easy?

The Lunar Night Survival Problem

- What can we do to make survival easier?
  - Perform lots of R&D making components capable of surviving extreme temperatures
  - Provide more onboard energy storage
  - Provide some type of offboard energy storage
  - Find points on the lunar surface that have shorter shadowed periods

The Lunar Night Survival Problem

- What can we do to make survival easier?
  - Perform lots of R&D making components capable of surviving extreme temperatures
  - **Provide more onboard energy storage**
  - Provide some type of offboard energy storage
  - **Find points on the lunar surface that have shorter shadowed periods**

The Lunar Night Survival Problem

- Provide more onboard energy storage
  - Add more batteries? Fuel cell? Perhaps… a radioisotope power system?
- Find points on the lunar surface that have shorter shadowed periods
  - More beneficial than one would think
  - A *significant* amount of work has gone into this; browsing available literature is highly recommended
  - For LTV, select amount of landing sites identified that allow for a reduced night-survival time: ≈125 hours rather than >350 hours
  - In this examination; LTV requested vehicle sizing analysis using a 125-hour night survival

The Lunar Night Survival Problem

- Where does RPS come into play regarding LTV?
- Early LTV analysis was showing high nighttime heat leaks
- Required energy to survive night periods greatly outpaced maximum hot traverse energy requirements; RPS could have a positive impact

Nighttime Heat Deficit	Length of Night Survival	Required energy
204 W_{th} 6.3 W_e	125 hr	26.3 kWh

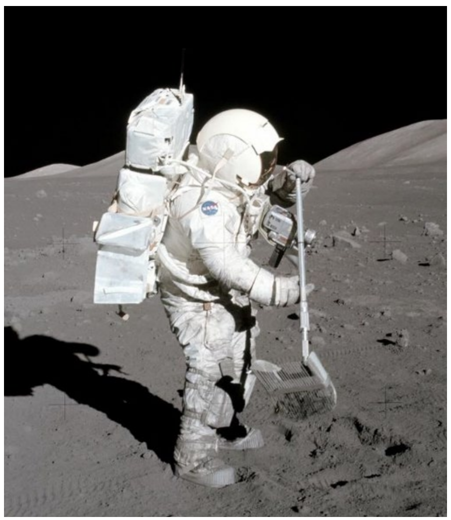
Category	Hot Traverse Power (estimates)	Length of Traverse ("emergency traverse back to base")	Required energy
GNC	100 W		
Crew systems	566 W		
Tool cart (sample storage, etc.)	803 W		
Display/Controls	56 W		
Avionics	213 W		
Propulsion (15 km/hr, 20 deg slope)	11,344 W		
Total	13,082 W	80 min (1.3 hr)	17.4 kWh

Background on Radioactivity

- Ionizing radiation → bad
  - Rays or high-speed particles with energy high enough to produce ionization
  - Dangerous to human crew – can break molecular bonds, damage DNA
  - Difficult to dose, inherently random process
  - Not great for science either: instrument noise, chipset damage
  - Transforms from unstable isotope down decay chain, eventually to stable isotope
- Non-ionizing radiation → not so bad
  - Cell phones, microwaves, WiFi

Background on Radioactivity

- Decay occurs through four methods that have different penetrating power
  - Alpha, α (can be stopped by paper)
  - Beta, β (can be stopped by thin sheet of metal)
  - Gamma, γ (can be stopped with inches/feet of material)
  - Neutron; needs exceptionally thick shielding. Can also induce radioactivity in other materials via neutron activation.



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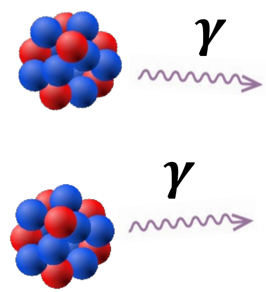

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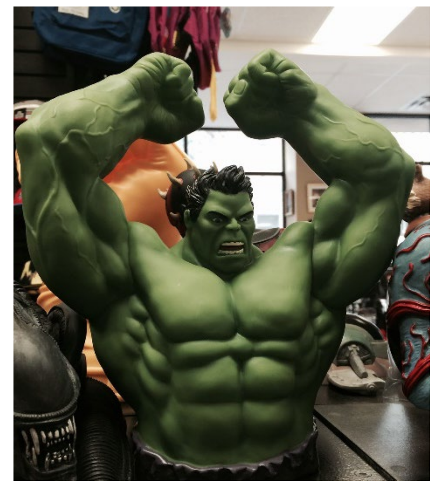

Image by ErikaWittlieb

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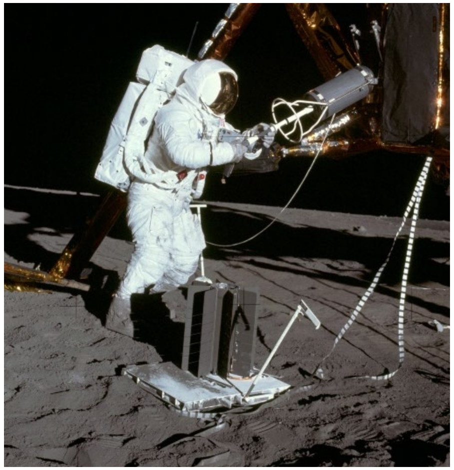
- Isotopes with primarily alpha emission preferable for spacecraft due to lower shielding requirements (less mass, safer for crew)

Radioisotope Flight Heritage

- SNAP-3 RTG powers Transit 4A in earth orbit (1961; Pu^{238})
- Soviet Lunokhod rovers utilize radioisotope heat sources (1969-1077; Po^{210})
- SNAP-27 RTG powers ALSEP (Apollo 12-17; Pu^{238})
- Various SNAP-19 RTGs power Pioneer and Viking probes (Pu^{238})
- MHW-RTG powers Voyager 1 & 2 (1977, Pu^{238})
- GPHS-RTG powers Galileo (1989), Cassini-Huygens (1997), Ulysses (1990), and New Horizons (2006); all Pu^{238}
- Chinese Chang'e-3/Yutu lander and rover have RPS (2013, Pu^{238})
- Various radioisotope systems on all Mars rovers; Sojourner, Spirit, Opportunity, Curiosity, Perseverance (all Pu^{238})



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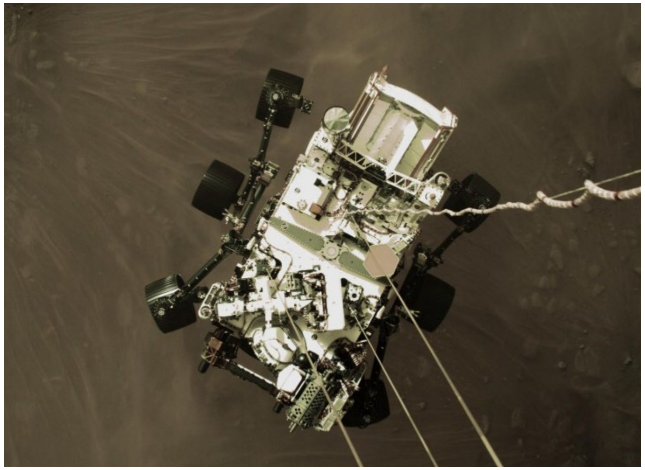
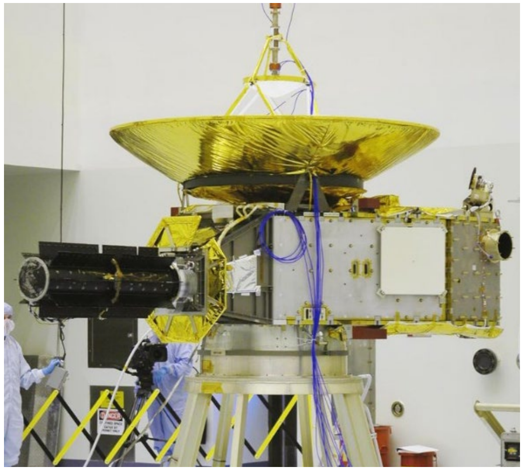


NASA/JPL-Caltech



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Isotope Selection

- Spacecraft pose unique challenges that significantly affect isotope selection
- Isotopes must be:
  - Long lived (long half-life)
  - Easily shielded
  - High thermal output per unit mass
  - Relatively plentiful, or producible at the kilogram level
- Out of 1300 isotopes, ≈30 are applicable
  - If limited to:
    - 100 days < $T_{1/2}$ < 100 years half-life
    - Specific power > 0.1 W_{th}/g
    - Eliminating most gamma-producing elements
- Of these 30, only 8 isotopes have generally received spaceflight interest (see next slide)

Isotope Selection

Isotopic Compound	Main emission	$T_{1/2}$ [yr]	Spontaneous Fission (FS) $T_{1/2}$ [yr]	Melting Point [°F]	Density [g/cm^3]	Specific Power [Wth/gm]	Activity per Watt(th) [Ci/Wth]	Pb Shield thickness [in]
$Pu^{238}O_2$	α	87.7	$5x10^{10}$	4,352	10.0	0.39	30	0.1
$Am^{241}O_2$	α	432.0	$2x10^{14}$	3,632	10.47	0.097	30	0.7
$Cm^{244}{}_2O_2$	α	18.1	$1.4x10^{7}$	3,956	9.0	2.27	29	2.01
$Cs^{137}Cl$	β^-	30.0	-	1,193	3.2	0.12	207	4.6
$Sr^{90}TiO_2$	β^-	28.0	-	3,704	4.6	0.22	148	6.0
Metallic Co^{60}	γ	5.24	-	2,723	8.8	1.74	65	9.5

M. Ragheb, "Radioisotopes Power Production," 15 February 2011. [Online]. Available: http://large.stanford.edu/courses/2011/ph241/yemane1/docs/ragheb.pdf. [Accessed 26 October 2021].

- M. Ragheb lists required lead shielding thickness for $1kW_{th}$ output at effective (dose equivalent) if 10 mrem/hr at 1m
  - Dose is not particularly relevant here, but terrestrial radiation worker limit is 5 rem/yr
- Difference in shielding for emission type is obvious, with Co^{60} requiring 95x more shielding than $Pu^{238}O_2$
- Programmatic concerns start popping up; high melting points desirable in event of launch failure, non-soluble compounds desirable in event of accidental dispersion

Isotope Selection

- Commercial startups promising more efficient products with less bureaucracy often look good on paper
  - Ultimately, most commercial endeavors fall short on their promises
  - Many isotopes seem perfect on paper but falter when considering chemical packaging, shielding requirements, lead time, half-life, production paths, etc.
- In short, it is clear why $Pu^{238}O_2$ is the isotope of choice for America's space programs; it has a long half-life, low shielding needs, high specific power, can be produced at the kilogram level, etc.
- Am^{241} is likely the next most spaceflight-worthy candidate; subject of continued research in Europe.
- Po^{210} also has spaceflight heritage on USSR Lunokhod-class rovers

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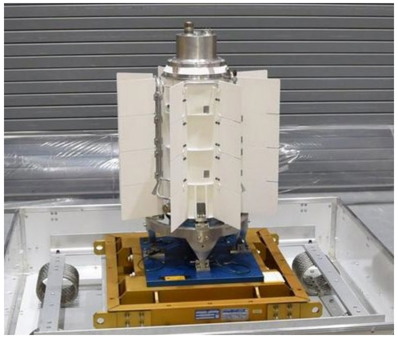
Current/Near-Term Radioisotope Systems

- Literature review examined what systems are currently available for spacecraft use or available in "near-term" (next decade)
  - Multi-Mission Radioisotope Thermal Generator (MMRTG)
    - Flown on 2x Mars missions (Curiosity, Perseverance)
    - Thermal and electrical generator
  - ½ sized MMRTG
    - Proposed system with ≈1/2 output and size of MMRTG
  - Radioisotope Heating Units (RHUs)
    - Film-canister sized units that output ≈1 W_{th} each
    - Flown on many missions; usually provides local heating at vehicle extremities
  - 2-Module GPHS-RHU
    - Proposed system offering higher thermal density than RHU, but without electrical generation of RTGs
  - Stirling Radioisotope Generator
    - Next-gen MMRTG replacement; offers more electrical generation with much less thermal output
  - Chargeable atomic batteries
    - Take non-radioactive materials, place them in fission reactor and use neutron activation to make them radioactive
  - "Commercial RHUs"
    - Variety of products proposed by startup companies
    - Generally RHU-like (only thermal output)
    - Variety of isotopes, production paths (fission reactor waste)
    - Omitted these due to low TRL



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MMRTG

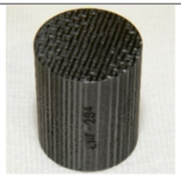
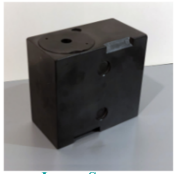
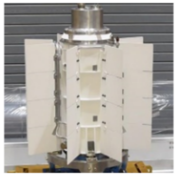
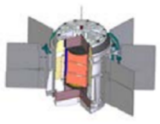
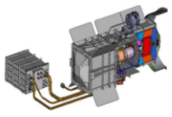
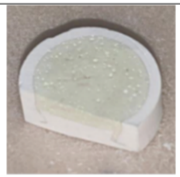
RHU

Image Source

Image Source

Stirling Radioisotope Generator

Analysis Downselection

Power System Type	Batteries (Baseline)	Radioisotope Heating Unit (RHU)	2-Module GPHS-RHU	Multi-Mission Radioisotope Thermal Generator (MMRTG)	½ size MMRTG	Stirling Radioisotope Generator	Chargeable Atomic Batteries
Depiction		 Image Source	 Image Source		 Image Source	 Image Source	 Image Source
Source	Commercial vendor	NRC or DOE	NRC or DOE	NRC or DOE	NRC or DOE	NRC or DOE	Commercial vendor
Development Status	Flight heritage	Flown	Proposed	Flown	Proposed	In development	Proposed
Electrical Output	N/A	None	None	108 W_e (BOM) [5]	54 (BOM, assumed)	137 W_e (BOM)	Unknown (watts)
Electrical Output	N/A	None	None	66 W_e (EOM)	33 W_e (EOM, assumed)	122 W_e (EOM)	Unknown (watts)
Thermal Output (BOM)	N/A	1.0 – 1.1 W_{th}	488 W_{th} (BOM)	1892 W_{th} (BOM)	946 W_{th} (BOM, assumed)	330 W_{th} (BOM)	Unknown (watts to kilowatts)
Thermal Output (EOM)	N/A	<1 W_{th}	451 W_{th} (EOM)	1751 W_{th} (EOM, assumed)	875 W_{th} (EOM, assumed)	299 W_{th} (EOM, assumed)	Unknown (watts to kilowatts)
Mass	N/A	40 g each	6 kg	45 kg	23 kg (assumed)	Unknown	Unknown
Radiation Risk/Shielding Requirements	None	Low	Low	Low	Low	Low	Medium/High
Lead Time	Months	2 years for new production (56 RHUs in storage)	5-6 years (estimate)	5-6 years	Unknown	By 2028 [6]	Unknown
Cost Impact	Low	High	High	High	High	High	Medium
Minimally feasible for LTV	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Feasibility estimation, limiting factor	Medium (mass limitations)	High	Medium (development time)	High	Medium (development time)	Low (proof of concept)	Low (proof of concept, shielding mass)

Analysis Downselection

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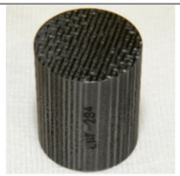
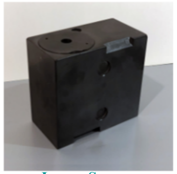
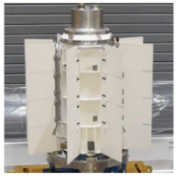
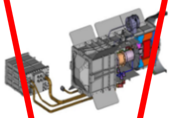
Depiction		 Image Source	 Image Source		Image Source		 Image Source
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Captured in MMRTG analysis

Development time too long

Not enough detail/high enough TRL

How to Analyze Benefits?

- RPS pose interesting issue in trade-space - they can be considered "infinite" power/thermal sources
- How to perform trade study?
  - In case of LTV, cost or bureaucratic complexity could not be factors since the project seeks contractor proposals (i.e. it is often assumed the contractor would bear the burden of managing extra complexity)
  - However, *mass* was (and is) a major influence on vehicle design space

RHUs vs. Batteries:

- Specific power of RHU at end of 10-year LTV life: 20.8 W_{th}/kg
  - 48g of RHU needed to supply 1W heat over 125-hour night
- Estimated battery energy density at end of LTV life: 74 Wh/kg
  - 1.69 kg of batteries needed to power 1W heater over 125-hour night
- Comparing RHU vs. batteries shows RHU's are over 35x more efficient on a per-mass basis than batteries for thermal delivery

How to Analyze Benefits?

RTGs vs. Batteries:

- Specific power of MMRTG: ≈1.2 W_e/kg
- Specific power of solar arrays: ≈ 25 W_e/kg
- Solar arrays clearly win out… so why use an RTG?
  - Continuous production of power
  - Continuous thermal output
  - Less energy storage need (less battery mass)
- RTG Drawbacks
  - Relatively low electrical output: 60-110 W_e
  - Would take *24 days* to recharge proposed 32 kWh stack at end-of-mission output
  - Not fast enough recharge capability for multiple traverses in short span: NASA requested 8-hour duration of use per 24-hour period
  - **An RTG on LTV could only supplement a solar array, not replace it**

LTV Trade Study

- Should we use an RTG? Just RHUs? Combine RHUs and RTG? Is there an optimum mix?
- Proposed to look at seven cases:
  - Case 1: Baseline, battery/solar power
  - Case 2: Add enough RHUs to make traverse limit battery size
  - Case 3: Add enough RHUs to eliminate nighttime heat leak
  - Case 4: Add GPHS-RHU to see if it is more efficient mass-wise
  - Case 5: Case 3, but add ability to charge during traverses with solar array
  - Case 6: MMRTG + batteries + solar array
  - Case 7: ½ size MMRTG + batteries + solar array

LTV Trade Study Results

Case#	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Description	Baseline (batteries + solar)	Balance RHU to traverse needs	Full RHUs	GPHS-RHU	3kW charge during traverse + Full RHUs	MMRTG	½ size MMRTG
RTG/RHU thermal addition	N/A	70.8 W_{th}	204 W_{th}	451 W_{th}	204 W_{th}	1751 W_{th}	875 W_{th}
Battery energy required	26.3 kWh	17.4 kWh	17.4 kWh	17.4 kWh	13.4 kWh	17.4 kWh	17.4 kWh
Energy surplus at night?	No	No	133 W	133 W	101 W	199 W	166 W
Mass improvement	N/A	105 kg	94 kg	103 kg	113 kg	55 kg	82 kg

- RPS offered *significant* mass improvement in all cases examined
- Most cases were eventually limited by battery energy required for traverse
  - At that point, the only option to reduce battery mass further is to design a solar array that will allow charging during traverses
  - Such an array would add significant mass as it would have to track sun location and be highly damped

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Mass improvement	N/A	105 kg	94 kg	103 kg	113 kg	55 kg	82 kg

- Once battery size is limited traverse needs, proposed LTV becomes power-positive during night survival
- Offers capability to perform additional science, potentially mobility operations
- MMRTG specifically useful because it could allow for battery *charging* overnight
  - Vehicle would not be limited by 125-hour night or even full >350-hour night: could traverse *anywhere* on the lunar surface within vehicle specifications
  - *AKA: Indefinite survival in permanently shadowed regions*

Conclusions

- Radioisotope power systems have significant flight heritage spanning the last 60 years.
- RPS drawbacks are usually not technical in nature, but bureaucratic; their engineering uses are well understood, but come with intense programmatic investment.
- Only a few isotopes are optimized for spaceflight; primarily alpha emitters; others usually incur mass penalty due to shielding needs.
  - Pu^{238} remains the isotope of choice for most spacecraft due to its long half-life, high thermal output, and ability to meet safety demands.
  - Commercial vendors using other isotopes may be less expensive or more readily available (eventually), but impacts should be well understood.
- RHUs and RTGs can save significant system mass on lunar vehicles by reducing or eliminating nighttime battery power needs.
  - In the case of a proposed LTV, RHUs or RTGs could save 50-110kg of mass from baseline predictions.
- For crewed rovers, RTGs should offer supplemental power to solar arrays
- Radioisotope power systems can unlock indefinite night survival for lunar systems; a key capability that aligns with America’s spaceflight goals.

Questions?