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

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Spacecraft thermal environments tend to be extreme, and the lunar surface is no exception. Future lunar missions aim to explore the lunar south pole region, focusing on permanently shadowed region (PSRs) that may act as cold traps for volatile elements such as hydrogen. By careful selection of landing sites, the longest continuous period devoid of insolation near these PSRs can be reduced significantly from the maximum of 354 hours. Future NASA missions aim to allow exploration of PSRs with a crewed lunar rover. Program architectures may impose a requirement that the vehicle be able to survive repeated lunar nights. Surface temperatures at southern latitudes can be lower than 100K during night, causing significant energy demands heating components above keep-alive temperatures. This adversely affects lunar programs which are heavily mass-constrained. A technical exploration of various radioisotope power systems and their viability, benefits, and drawbacks was completed. An analysis was also performed examining potential vehicular mass reduction and increased lunar night survivability due to the inclusion of radioisotope power sources. The results of this analysis were compared to a baseline non-nuclear vehicle utilizing only batteries and solar arrays for energy storage.

Nomenclature

ASRG	=	Advanced Stirling Radioisotope Generator
BOM	=	beginning of mission (typically 3 years after RPS fueling)
DOE	=	United States Department of Energy
eMMRTG	=	Enhanced Multi-Mission Radioisotope Thermoelectric Generator
EOM	=	End of mission (10 year LTV life)
EOVL	=	End of vehicle life
GNC	=	Guidance, navigation, and control systems
GPHS	=	General-purpose heat source
LTV	=	Lunar Terrain Vehicle
MMRTG	=	Multi-Mission Radioisotope Thermoelectric Generator
NASA	=	National Aeronautics and Space Administration
NRC	=	United States Nuclear Regulatory Commission
PSR	=	Permanently shadowed regions
RHU	=	Radioisotope Heater Unit
RTG	=	Radioisotope Thermoelectric Generator
STEM-RTG	=	Segmented Thermoelectric & Modular Radioisotope Thermoelectric Generator
W_e	=	Electrical power
W_{th}	=	Thermal output

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I. Background

THIS white paper is intended to perform a cursory examination of various radioisotope heating and power solutions and their impact on the Lunar Terrain Vehicle (LTV) as a whole. The proposed LTV combines the transport capabilities utilized in Apollo-era crewed lunar rovers with scientific instruments generally seen on uncrewed planetary rovers that allow imaging, mapping, sample return, etc. A substantial engineering challenge exists regarding surviving both the lunar day and the lunar night, but particular challenges exist in surviving the cold and lengthy lunar night. One of the more promising solutions identified was the use of radioisotope power systems to heat or provide energy to the vehicle when in lunar night. These systems were not fully understood in the context of LTV; this paper intends to provide a review of existing or planned radioisotope systems and examine their potential uses on the vehicle or future similar lunar vehicles.

II. The Lunar Night Survival Problem

A. The Lunar Environment

Without an atmosphere with which to sink substantial thermal energy or geologic activity creating appreciable geothermal heating, surface temperatures on the Moon are heavily dependent on insolation (that is, the amount of solar radiation an area experiences). Areas in direct sunlight quickly reach high temperatures, while areas in shadow or lunar night drop to very low temperatures. Not only do these daily temperature extremes exist – they are present for very long durations. A traditional lunar day/night cycle lasts 29.53 Earth days with the day and night each taking half that time or about 356 hours [1]. With carefully selected landing sites the exact periods of day or night are often different due to a multitude of factors (orbit of the moon, latitude, elevation of the selected site, and other variables). A select amount of landing sites have been identified at the lunar south pole where the maximum length of lunar night local to the site does not exceed 125 hours in length across an expected 10-year vehicle operating life. It is this length of time – 125 hours – that engineers are currently using in the process of sizing a lunar terrain vehicle, or LTV.

Temperatures on the moon, whether they represent the surface itself or a particular portion of a vehicle, are in themselves difficult to estimate. Surface and component temperatures will vary based on solar incident angle, latitude, regolith thermophysical and optical properties, time of year (season), time of day, both global (e.g. maria vs. highlands) and local (e.g. craters, valleys) geological features, planetshine, and a host of other variables. Of these, perhaps the most important to the thermal engineer are surface optical properties. These optical properties define how much solar flux will be absorbed and how easily much energy is emitted from the object in the form of infrared radiation (heat). Thus, a component's maximum temperature is dependent on these properties and varies widely in the general range of 100 – 300 °C. Cold temperatures are slightly easier to estimate as insolation is not a factor. Still, they are similarly extreme; temperatures at the lunar south pole can dip as low as 25K in permanently shadowed regions (but remain higher throughout most of the polar region). All this to say: lunar thermal analysis is complicated and there is rarely a single temperature that will represent a particular environment or bounding condition.

Thermal management on the lunar surface is generally limited by the fact the moon has no atmosphere. This limits heat transfer paths to radiation and conduction. The lunar surface is generally a poor thermal conductor and it would make little sense to require a strong thermal tie between a moving vehicle and lunar regolith, which leaves radiation as the main source of heat transfer available to LTV designs.

For most potential vehicles, the lunar surface environment is very extreme in both day and night cycles. When exposed to harsh sunlight in the daytime, a vehicle will most likely require one or more onboard radiators with a direct view to deep space with which to reject heat. Failing to reject heat leads to component overheating, lifespan degradation, and potential failure. In the nighttime, this is reversed; in order to survive the harsh cold environment it becomes beneficial to reduce components view to space as much as possible and use insulation to minimize heat loss to the environment.

B. Operation of Electronics

The low temperatures discussed in this paper are at times difficult to conceptualize. For some degree of reference, the lowest natural temperature on Earth (measured directly and at ground level), is -89.2°C, or 184.0 K [2]. Night temperatures on the lunar south pole in locations where volatile exploration is desired often fall to as low as -233.2 °C (40 K). Such frigid temperatures pose a challenge for most electronics, whether or not they are consumer or industrial-grade. These low temperatures can cause electric signaling to run out of phase, stress to accumulate on circuit boards due to thermal expansion and contraction, freezing of electrolyte materials, etc. The variety of failure types precludes the ability to simply let some electrical components fully hibernate during a night and sink to low temperatures – once exposed to a low enough temperature, many components simply will not operate when brought up to a more reasonable environment.

Thus, there exists some impetus to keep electronic components at a relatively constant and warm temperature during all phases of operation. This, in essence, drives the project towards a continuously active vehicle – fully turning off the vehicle in a cold environment would certainly jeopardize its ability to return to operation in the future.

While electronic components are the lowest hanging fruit regarding component failures due to temperature, they are not the only components on the vehicle sensitive to temperature changes. Certain structural or mobility elements such as joints and motor drives are additionally sensitive to temperature because of thermal contraction and increased viscosity or freezing of lubricants at low temperatures. Maintaining operation of any bulk structural elements such as trusses, seating, and supports is generally feasible across wide temperature ranges, but additional heating sources may be required at key interfaces or components.

C. Surviving Lunar Night

From a thermal engineering perspective, the lunar day/night cycle requires a specific balance to be identified and the vehicle optimized to meet that balance. It is helpful to discuss the competing requirements of thermal isolation, insulation, radiative & conductive heat loss. Unfortunately, surviving the lunar night would be relatively easy if one did not also have to survive the lunar day as well. During a lunar night, it is necessary to thermally isolate components so they maintain survivable temperatures and do not conduct or radiate heat to the environment (which would cause additional heater needs). However, during the, day the vehicle is exposed to solar flux - warming components to the point that excess heat must be rejected from the vehicle. This cannot occur if components are excessively thermally isolated. This results in a significant dichotomy in terms of vehicle design – components must be warmed in cold environments and cooled in hot ones, all with a single vehicle thermal management system.

Putting the difficulty of identifying the most optimized balance aside, early analysis showed that the LTV is significantly night-challenged. The extreme cold of the environment quickly cools the vehicle, requiring heaters be added to keep components at survival temperatures. These heaters require electric power which must be delivered by batteries, which add to the vehicle mass. One early LTV proposal aiming for a total vehicle mass of 500 kg found that >400 kg of battery mass was required to survive the night. At that point, a campaign began to investigate heat leak sources in thermal models and modify the design in a way that minimizes them, with the ultimate goal of reducing vehicle mass.

Heat leak is considered to be any heat that radiates or conducts away from the vehicle that is lost to the environment. Although conduction paths to the environment are present in the form of wheels contacting the lunar regolith, it is expected that the largest form of heat leak from the vehicle will be radiation to deep space and the surrounding environment.

$$Q_{rad} = \varepsilon\sigma A({T_{obj}}^4 - T_{env}^4)$$

The above equation shows the Stefan-Boltzmann law, which is used to calculate the amount of radiative heat transfer from a black body object to the environment. The amount of heat transferred via radiation (Q_{rad}) is dependent on the surface property emissivity (ε), the Stefan-Boltzmann constant (σ), surface area of the object (A), absolute temperature of the object (T_{obj}), and the absolute temperature of the environment (T_{env}). It is this equation that allows for a relatively quick calculation of heat rejection (during lunar day) and survival heating (during lunar night) since conductive losses from the vehicle are expected to be minimal and there is no bulk fluid on the lunar surface with which convective losses may occur.

As can be seen in the Stefan-Boltzmann law, the desired temperature for an object is a significant driver of the amount heater power needed as the temperature of the object is weighted to the 4^{th} power. Since the LTV is in early stages of development, temperature limits of the vehicle are not well understood but can be assumed to comprise a relatively small (compared to the environment range 3K to >380K) range of approximately 250K to 330K. From this equation, it is seen that it is very beneficial – even within a limited temperature range – to select components with a wider range of operational and survival limits. Decreasing a component's survival temperature from 270K to 250K, for example, decreases heater power requirements by 26%; the same change would require a reduction in surface area by 26% or a significant change in surface property emissivity which would likely detrimentally impact heat rejection.

As just demonstrated, another significant driver for heater power is the surface area exposed to cold environments. For the current LTV design it was desirable to co-locate as many components as possible within the same hot box, thereby decreasing the amount of overall surface area exposed to the environment and decreasing the heater power needed to survive the lunar night.

D. Surviving the Lunar Day

As mentioned in the previous section, during the lunar day components once requiring heating or significant thermal isolation now require that heat to be offloaded or dissipated. This again requires a design methodology completely contradictory to that of a cold case; one where components dissipating heat generally need to be coupled to a radiator or directly view deep space with minimal insulation in order to remain at operational temperatures. Implementing creative measures of heat transfer is often required and significant thought must be placed behind every component, its purpose, operation, and location.

Unfortunately, a full examination of surviving a lunar day is left to future discussion. It is sufficient to say that hot-case performance is generally constrained by avionics maximum temperature limits, available radiator surface area, and the ability to conduct or pass heat to a radiator element. Naturally, the most ideal vehicle design is capable of separating this high-conductance path during nightfall in order to maintain the design balance necessary to also surviving the lunar night. With the main thermally limiting factor in LTV design being night survival, the radioisotope systems examined in future sections are examined in that context rather than their hot case performance. Relative impact on hot environments is acknowledged from an engineering judgement perspective, but analysis on the viability of any particular system in lunar day was not performed. The presence of any particular radioisotope system presented in this document should not be taken as an endorsement that it will produce a feasible design.

E. Potential Power Sources

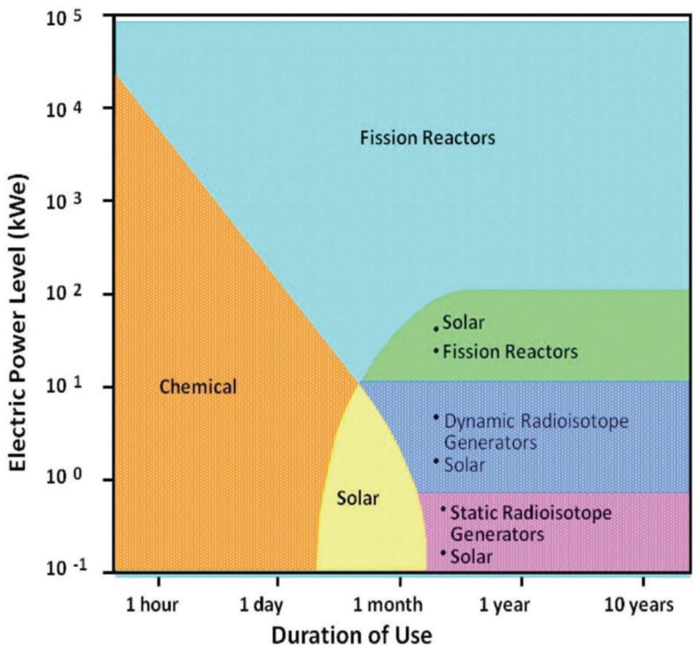


Figure II-1 [3]

While few power sources are available to spacecraft in general, lunar landers are particularly limited since they tend to be more mass-challenged than most spacecraft. As is seen in Figure II-1, the type of power generation on a vehicle is largely driven by duration of use and the electric power required by the vehicle. In the case of LTV, the long vehicle life of 10 years and low average electricity needs (between 10^{-1} and 10^{1} kWe) limits optimal power options to solar energy and dynamic or static radioisotope generators. Previous lunar landers and surface experiments have relied exclusively on these two power generation classes, reinforcing their fit for this document scope.

A literature review was performed to identify current and near-term (within the next decade) radioisotope power supplies applicable to a mission of this size. Fission reactors and chemical fuel cells were explicitly not considered due to scope, as were heritage radioisotope systems no longer in production. The literature review identified several potential candidates; in fact, too many candidates were identified than could be listed. A representative cross-section of the potential candidates was selected that was felt to encompass "minimally achievable" designs (i.e. designs with proven scientific background and a clear path to demonstration, not vaporware or thought experiments). The identified technologies are tabulated below along with the author's commentary on various programmatic factors such as cost, radiation shielding needs, and factors inhibiting implementation.

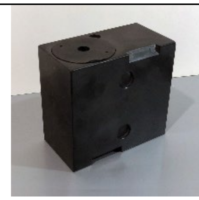
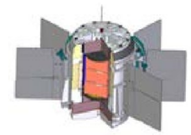
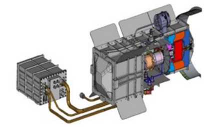
Power System Type	Batteries (Baseline)	Radioisotope Heating Unit (RHU)	2-Module GPHS-RHU	Multi-Mission Radioisotope Thermal Generator (MMRTG)	½ size MMRTG	Stirling Radioisotope Generator	Chargeable Atomic Batteries
Depiction		 [4]	 [5]		 [6]	 [7]	 [8]
Source	Commercial vendor	NRC or DOE	NRC or DOE	NRC 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) [6]	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 [7]	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)

Table II-1: Pertinent Current and Near Term Radioisotopic Power Supplies

III. Isotope Selection and Radioactivity

F. Background on Radiation

This paper is not intended to examine specific radioisotope systems and their applicability to crew safety or radiation dosage received. However, the amount of radiation shielding required to make a radioactive source tolerable for crewed use impacts both vehicle mass and thermal output per unit mass of radioisotope power systems. Because of these concerns, a brief (and by all means not comprehensive) discussion on radioactivity and shielding is presented.

Radioactivity is energy given off by matter in the form of rays or high-speed particles [9]. Radioactive elements are inherently unstable – radioactive emission is the manner in which excess atomic energy is expelled as the element proceeds through a decay chain ultimately to a stable daughter isotope. This emission, or decay, primarily occurs via four methods – alpha, beta, gamma, and neutron radiation. Alpha decay generally requires little shielding; the particles emitted are able to be stopped by a single sheet of paper or a few centimeters of air [9]. Beta decay is slightly more penetrating and can be stopped with a thin sheet of metal or block of wood [9]. Gamma rays can pierce several inches or feet into materials. Generally, thinner shielding (in the realm of inches) is viable if dense materials like lead or depleted uranium are used. X-ray radiation can also occur in some cases (often as a secondary effect called "bremsstrahlung") and is similar to gamma radiation in that they are both high-energy, high-penetrating waves. Neutron radiation is the most penetrating of the four types given here and requires very thick shielding. Neutron radiation can also induce radioactivity in other materials in a process called neutron activation.

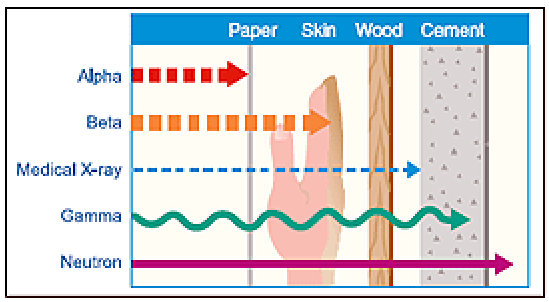


Figure III-1: Radiaton Type and Penetration Depth [9]

Ionizing radiation is dangerous to human crew as it has enough energy to break molecular bonds and displace (or remove) electrons from atoms. All the radiation types listed above – alpha, beta, gamma, X-ray, and neutron – are ionizing radiation. Exposure effects of ionizing radiation are generally twofold; high exposure can lead to direct cell or tissue death, and lengthy exposure can dramatically increase the lifetime risk of having cancer as it damages DNA molecules. Apart from crew safety, excessive radiation can also have effects on scientific instruments and can cause detector noise, damage to sensitive components (i.e. electronic chipsets and memory), single event failures, and more [10].

G. Isotope Selection Criteria and Radiation Shielding

Now that the basics of radiation have been discussed, we can investigate the selection criteria isotopes must meet in the context of a spacecraft. Isotopes must be long lived (i.e. long half-life), have a high thermal output per unit mass, be easily shielded, and be (relatively) plentiful or have a path to production at the kilogram level.

Nearly 1,300 radioactive isotopes both natural and manmade are available [11]. If one limits acceptable half-lives to 100 days < $T_{½}$ < 100 years, this number is reduced to approximately 100 isotopes [11]. Eliminating elements with powerful gamma radiation and taking those with specific power > 0.1 W_{th} per gram limits this list even further to around 30 isotopes. A detailed list of potentially suitable isotopes is presented in Ref. [11] (from which this selection criteria was referenced). Ultimately, only eight isotopes have generally received interest due to the combination of desirable characteristics and inexpensive production [11].

Isotopic Compound	Main emission	$T_{1/2}$ [yr]	Spontaneous Fission (FS) $T_{1/2}$ [yr]	Melting Point [°F]	Density [g/cm³]	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

Table III-1: Radioisotope Chemical Properties and Shielding Requirements [11]

A table from Ref. [11] lists required lead shielding required for various radioisotopic sources of 1 kW_{th} leading to an effective (dose equivalent) of 10 mrem/hr at 1 meter. The exact dose amount is not particularly relevant to this discussion, but radiation doses on Space Shuttle missions average approximately 433 mrem/mission while the highest skin dose experienced during the Shuttle program was 7,864 mrem/mission [12]. The dose limit for terrestrial radiation workers is 5 rem/year [12]. As is shown in the table, lead shielding thicknesses vary wildly depending on isotope. Strong gamma sources like Co^{60} require nearly two orders of magnitude more shielding than the alpha-emitting $Pu^{238}O_2$.

Chemical fuel form is also a contributing factor, as pure elemental forms of materials are often unsuitable for packaging. Radioactive isotopes are generally bonded in molecules to stabilize the fuel in terms of chemical reactivity. Optimal fuel forms generally have high melting temperatures so that fuel remains solid during fire scenarios, and are not soluble in fresh or salt water to reduce contamination if accidentally released into the environment. Structural stability is also considered to minimize radioactive contamination in the event of a catastrophic failure.

All of these factors combined strongly guide isotope selection. Many isotopes seem desirable on paper, but are less optimized when considering all factors such as chemical doping, main radioactive emission type, secondary bremsstrahlung effects, shielding requirements, cost, lead time, and half-life. Table III-1 above describes a (non-comprehensive) list of radioactive isotopes with bodies of research into their applicability for spaceflight. Given this table and the aforementioned isotope selection criteria, it is clear why $Pu^{238}O_2$ makes for a commonly selected isotope; it requires very little shielding, has a long half-life, high specific power, high melting point, and is produced at the kilogram level. Am^{241} is likely the next most probable candidate to be used in spacecraft and is the subject of continuing research for use in a European RTG or RHU. Other isotopes have little to no flight or proto-flight heritage, with the exception of Po^{210} which was used on the USSR Lunokhod-class rovers.

IV. Radioisotope Heating Units

H. Background

Radioisotope heating units, or RHUs[4], are quite simple devices that have a singular purpose: generate localized heat. A relatively standardized model for RHUs has come to prevalence over the years; a small cylinder containing just enough radioisotope material – specifically, Pu_{238} – to give off approximately 1 W_{th} of heat. The body of the device is comprised of interlocking cylinders for the protection of the device. Because very little heat is generated per RHU (1 W_{th} as opposed to a General Purpose Heat Source (GPHS) output of 250 W_{th}), they are quite small; the body of a "standard" RHU is only 1 inch in diameter by 1.3 inches high. Due to this portability, RHUs are traditionally placed in spacecraft to supplement heaters or provide heat to locations where heaters cannot easily be placed.

[4] RHUs are sometimes referred to as light-weight radioisotope heating units, or LWRHUs

Figure IV-1: Photograph of a Radioisotope Heater Unit [13]

I. Benefits and Complications

Energy density for a radioisotope material is much more difficult to estimate than that of batteries. The reason for this is simple: radioisotope elements do not "deplete" in the same manner as batteries. As all radioactive elements are defined by a half-life, energy output simply decays exponentially. There is no way to turn an RHU "off" or to exhaust the energy emitted other than the passage of time. For a short-lived vehicle (one substantially less than that of the radioisotope half-life), RHUs can be considered "infinite" sources of energy.

On paper, this "infinite" supply breaks traditional energy storage analysis, but a comparison can be made regarding mass allocation, which is particularly useful regarding mass-limited spacecraft. A traditional RHU produces 0.90 W of heat at beginning of life[5] with a mass of 40 grams (approximately 1.4 ounces). We then can calculate the heat production at the end of a 10-year life. Assuming the RHU isotope is Pu^{238} which has a half-life of 87.74 years [11] and using the following equation (where λ is the decay constant $ln(2)/\textit{half-life}$), it is estimated that the EOL thermal energy production of a 40-gram RHU is 0.83 W.

$$P = P_0 e^{-\lambda t} \text{ [14]}$$

Using this number, it is relatively trivial to identify the "specific power" of an RHU device. Specific power is assumed here to be reported in units of W_{th}/kg. Continuing the example given above, the specific power of a Pu^{238} RHU at EOVL is $0.83\ W/0.04\ kg$ or 20.8 W/kg. Extending this to the case of the LTV, the amount of bulk-RHU mass required to deliver 1W of thermal energy at EOVL for a period of 125 hr is 48.1 g. This methodology does neglect the additional mass required to mount an RHU, additional shielding that may be required, as well as any passive cooling mechanisms that may be required to implement in hot cases, but serves as an appropriate first pass estimate suitable for modeling and estimation purposes.

Current estimates put the LTV battery energy density at 153 Wh/kg at BOL and 74 Wh/kg at EOVL. With this as a reference we are able to calculate the amount of battery mass required to provide the same 1 W heat output at the end of the 10-year vehicle life. Using night-survival constraint of 125 hrs of continuous darkness, the end-of-life battery energy density, and ignoring any "preheating" effects[6] that impact this time, a total of 1.69 kg of battery mass is required to power this hypothetical heater over the course of a lunar night. Similar to the RHU, this is a first-pass

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[5] Traditionally, 1.0 Wt_h is the reported heat output; a September 2014 review of the RHUs in the current DOE inventory reported an average thermal output of 0.90 W_{th}. Recent (October 2021) meetings with RPS-office officials suggest the current complement of RHUs in long-term storage are producing approximately 0.8 W_{th}

[6] By heating components to their maximum operating or survival temperatures just prior to nightfall, thermal inertia lengthens the time it takes to reach a steady state, reducing total heater energy usage

estimate and secondary mass effects such as additional wiring, patch heater mounting, heater control circuitry, etc. are explicitly ignored[7].

Though specific power and energy density cannot be directly compared to each other, mass can be. With the "night survival" example of these technologies, RHUs are favorable from a mass perspective. The same heater energy can be provided during a lunar night with 1.69 kg of batteries or 0.048 kg of RHUs, placing the applied energy vs. mass ratio of batteries at over 35 times that of RHU technology.

V. Radioisotope Thermoelectric Generators

J. Background

Radioisotope Thermoelectric Generators (RTG), unlike Radioisotope Heater Units, utilize the heat generated through the decay of radioactive materials to generate usable electric power. In general, RTGs utilize the Seebeck effect to convert heat to electrical energy [6]. RTGs have been used in many missions, but are perhaps most widely known for their use on deep-space spacecraft such as *Cassini* and Martian rovers *Curiosity* and *Perseverance*. RTGs in one form or another have been in use since the early 1960s, so the technology is well understood and has significant flight heritage.

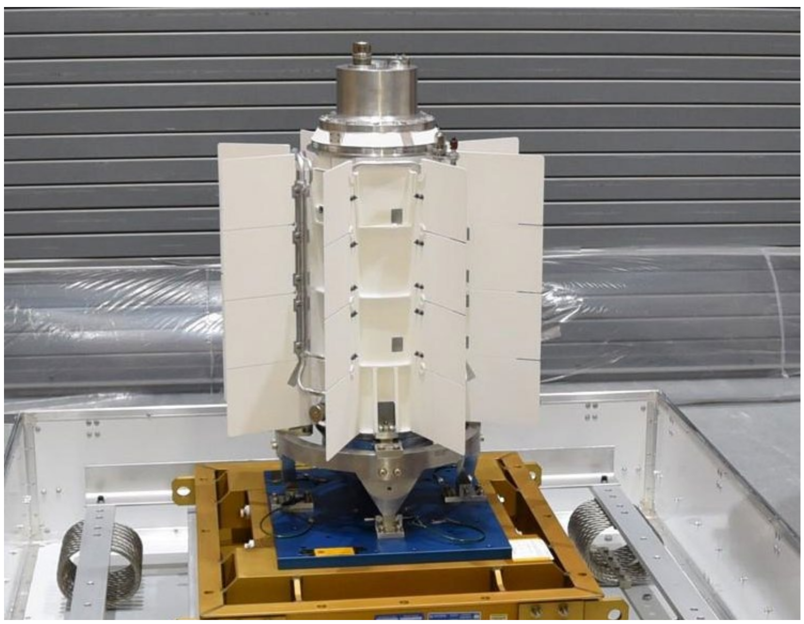

Figure V-1: Photograph of an MMRTG

K. Electrical Power Generation

One of the most beneficial effects an RTG has is that of constant, guaranteed electrical power generation. Currently-built Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) designs are able to produce 108 W of electrical energy at the beginning of a mission, reducing to 55 W after 17 years of use [6]. With an electrical power reduction of 4.8% year over year, we can estimate that a similar MMRTG if used on the LTV would produce approximately 66 W of electrical energy at the end of a 10-year mission.

It is clear examining these numbers that they are nowhere near the level needed to provide for the instantaneous power needs of the proposed LTV, estimated to be 13 kW as the rover climbs a slope at maximum speed. Luckily, combined with some other form of energy storage, an MMRTG would not need to meet instantaneous power delivery needs alone. For example, the *Perseverance* rover on the Martian surface has two battery banks totaling approximately 2.4 kW-h in energy storage from which the rover can dip into when needed [15].

However, examining the power needs of the proposed LTV relative to that of the *Perseverance* rover yields large discrepancies. Indeed, it is a testament to the engineering behind the Martian rover that it can be powered by such a small energy source and battery bank. The MMRTG power delivery of ≈100 W is similar to that of an incandescent

[7] The assembly-level packaging mass of batteries is captured in the reported energy density number

floodlight, and the 2.4 kWh battery bank similar to that in an electric riding lawn mower certified for 1.5 hours of continuous use [16]. The proposed LTV battery capacity is an order of magnitude above *Perseverance* at a currently-estimated 32 kWh, highlighting the fact that though these vehicles are similar in size and mass, they are simply in different classes in terms of intended usage. Recharging the full *Perseverance* battery stack from zero charge with an EOL MMRTG would take ≈ 44 hours (assuming no conversion losses). Doing the same with the LTV stack would take ≈ 582 hours or slightly above *24 days* – a number that is simply unacceptable given the planned mission operations.

It is clear that if an MMRTG would be used on LTV it would operate as a supplement to other power sources and not be the sole power delivery system onboard. With a mass of 45 kg, the specific power of an MMRTG system is approximately 1.2 W_e/kg. For comparison, rigid solar arrays used on the Tracking and Data Relay Satellite (TDRS) have a specific power of 25 W_e/kg [17]. Solar arrays are the clear winner on specific power alone but are limited in when they produce power, adding complexity to the trade space.

L. Benefits and Complications

Other complications of the MMRTG other than the thermal ones described previously include instrumental interference and integration difficulty. The design of the MMRTG results in electrical currents being present within the device, which in turn produce external magnetic fields. While these fields are not particularly strong, they may impact sensitive scientific instrumentation. Current guidelines also require the MMRTG to be integrated into the spacecraft at the launch site [6]. This requires additional planning so that the launch vehicle supports this last-minute integration. In the case of the Mars Science Laboratory (the *Curiosity* rover), the launch vehicle was stacked prior to MMRTG integration and a special fairing fabricated to allow the device to be integrated before launch. One benefit of using MMRTG technology is that it has no moving parts – significantly reducing potential points of failure as well as not impeding vibration-sensitive instruments such as seismometers.

Lastly - obtaining an MMRTG (or any assumed future RTG technology) is no easy feat. Plutonium-238 is costly and produced in very small amounts – U.S. production is in the process of ramping to a level of 1-2 kg per year. An MMRTG requires multiple kilograms of plutonium, which can add years to a schedule. In general, sourcing an MMRTG can take six or more years.

M. Future Systems

Future RTG technologies that build on the MMRTG concept are in development. These systems mainly attempt to optimize the current RTG concept via differing thermocouple designs and produce more power from the same thermal output. This class of future systems – which consists of the "enhanced" MMRTG (eMMRTG) and STEM-RTG – were not considered in this paper as they simply increase the amount of constant electric power available which was found to not be a main driver in required battery mass.

VI. Dynamic Radioisotope Generators

N. Background

Dynamic radioisotope generator technology has been proven in laboratory environments but has not been demonstrated onboard spacecraft. Dynamic radioisotope generators are fundamentally different than RTGs in one way: rather than using static thermocouples to generate electricity, dynamic generators use moving components.

While there are many different methods to creating a dynamic radioisotope generator, perhaps the most researched is the Stirling-cycle-converter. A Stirling cycle generator uses heated gas to move a piston carrying a magnet back and forth. The varying magnetic field is then able to be converted into usable electricity. Dynamic radioisotope generators are considered the next "class" in radioisotope power technology due to their efficiency; a Stirling cycle is approximately four times as efficient as thermoelectric conversion at 23% efficiency rather than 5-7% for thermoelectric technology [7].

O. Advanced Stirling Radioisotope Generator

The Advanced Stirling Radioisotope Generator (ASRG) is the most mature technology in the Stirling radioisotope generator family of technologies [6]. While funding for a flight unit was cut in 2013, engineering units were produced and have undergone more than 33,000 hours of testing [7]. The ASRG would consist of four main subsystems: GPHS modules, two power converters, a controller, and the general housing/heat rejection structure [6].

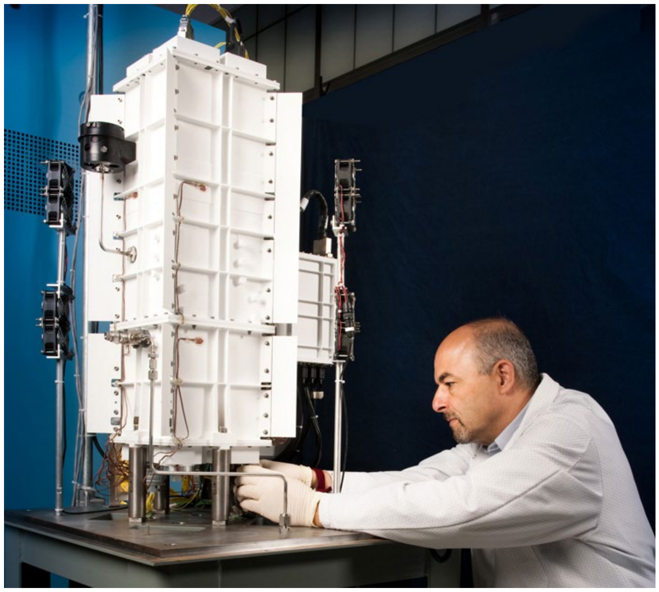

Figure VI-1: Photograph of ASRG Engineering Unit [18]

A potential drawback of the ASRG is actually a result of its higher efficiency. Because it requires much less radioactive material to produce the same amount of power as MMRTGs, the operational temperature is considerably lower. The MMRTG produces excess heat at 210 °C whereas the ASRG does so at 80 °C [7]. This comparatively low temperature makes it more difficult to reject heat via radiative heat transfer alone; the main mechanism available for lunar vehicles. Additionally, an MMRTG would more easily heat components during the lunar night due to its high operational temperature. On the other hand, the lower temperatures of an ASRG would be beneficial for aeroshell integration or spacecraft instrumentation sensitive to waste heat [7].

Another potential drawback of dynamic radioisotope systems is vibration and unwanted motion. Because these dynamic systems have moving parts, disturbance forces can be passed to the vehicle if tight control is not exerted over inertial forces within the device. Such vibrations may have a detrimental impact on science instrumentation, notably seismometers, cameras, and some spectrometers. The vibration from the ASRG has been tested and concluded that jitter is within the bounds of sensitive flight missions [10]. However, a contingency plan is recommended for configurations using an ASRG as one of the two Stirling engines may fail leading to an unbalanced device [10].

Many different dynamic radioisotope generators have been proposed and their particular thermal and electrical outputs may tailor them for specific missions. Unfortunately, there are too many proposed systems to list and compare here. Instead, relevant performance values for the ASRG are presented below and compared to the MMRTG. This allows for the relative benefits of dynamic systems over static ones to be seen.

	MMRTG	**ASRG**
Power Output	108 W_e (BOM) [6]	137 W_e (BOM) [6]
	55 W_e (EOM, 17 years) [6]	115 W_e (EOM, 17 years) [6]
Thermal Output	1892 W_{th} (BOM) [6]	330 W_{th} (BOM) [6]
	1697 W_{th} (EOM, 17 years) [6]	288 W_{th} (EOM, 17 years) [6]
Mass	45 kg [6]	31 kg [6]

Table VI-1

VII. Lunar Terrain Vehicle Radioisotope Application

P. Vehicle Setups Examined

A campaign was undertaken to estimate the mass impacts of adding radioisotope power systems to the LTV and whether those systems resulted in mass savings or any other additional benefits to the vehicle architecture. Several different types of radioisotope power systems and implementations were examined, resulting in the following case matrix. Each case name is followed with a short description and rationale for its inclusion:

1. Baseline LTV
    - Baseline LTV, utilizing only battery power during traverse and night survival. This provides an estimate for battery mass and volume in the least-complicated scenario.
2. Balanced RHUs
    - LTV relies on only battery power during traverse and night survival, but with enough RHUs added onboard to balance nighttime heater power usage with the minimum required battery size for traverses. This case should minimize the number of RHUs required while not increasing battery mass required.
3. Full RHUs
    - LTV relies on only battery power during traverse and night survival, but with enough RHUs to balance nighttime heat deficit. This case assumes no resistive heater elements are used and the battery is only used to support hibernation power load. Any energy surplus could be utilized for additional operations at night, limited by the battery capacity. This case assumes 100% of RHU thermal energy is directed to the vehicle and is not spilled offboard.
4. 2-Module GPHS RHU
    - LTV relies on only battery power during traverse and night survival, but has the additional heat load of a 2-Module GPHS RHU. Due to the high thermal output of the GPHS RHU, this case is similar to Full RHUs but the GPHS RHU is a centralized, compact system likely requiring a thermal distribution system. This case is expected to result in an energy surplus during lunar night similar to Case 3.
5. 3 kW charge during traverse + full RHUs
    - LTV relies on a combination of solar and battery power during traverse, and solely battery power during night. Heat deficit at night is eliminated with RHUs. This case assumes a constant 3 kW of power (60% of a proposed 5 kW array) is able to be produced during an 80 minute traverse. The ability to charge during traverse is currently being debated, but many cases involving radioisotope power systems became limited by traverse battery needs. This case examines if traverse power needs were lowered by simultaneous solar array use.
6. MMRTG
    - LTV relies on battery power plus constant MMRTG power production during traverse and night survival. Constant power production should decrease battery needs and create a fully power-positive vehicle at night, potentially opening up additional architectural capabilities (night operations, long stays in PSRs, et. cetera). Due to the high thermal output of the MMRTG, additional thermal distribution may be necessary as an MMRTG would need to be mounted external to the vehicle to reject excess heat.
7. ½ size MMRTG
    - LTV relies on battery power plus constant power production from a scaled down MMRTG during traverse and night survival. Power production with ½ size MMRTG would be limited, but enough to support hibernation load and some nighttime operations in conjunction with surplus battery energy. The thermal output of a ½ size MMRTG would be greatly reduced and easier to reject than a full-size MMRTG. The system would also require less mass than a full MMRTG.

Notably absent are any dynamic radioisotope power systems; because these systems are so similar to traditional RTGs as far as power generation and thermal output, results for cases 6 and 7 were expected to approximate most proposed dynamic devices.

Q. Analysis Methodology and Assumptions

To complete the analysis of the case matrix described above, a spreadsheet was made to calculate required battery masses while weighting in the effects of RHUs and RTGs. The energy requirements for the hot case traverse as well as the energy requirements for night survival were calculated for each case. These competing energy requirements are compared and whichever is greater used in the calculations for battery sizing. Thus, it is possible for the battery sizing to be constrained by the energy requirements of night survival (heater power needs, hibernation energy usage, etc.) or the energy requirements for traverse (powered GNC, crew systems, avionics, mobility elements, et. cetera). The assumptions for the traverse and hibernation power requirements are provided below.

Hot Traverse Power	
GNC (W)	100
Crew systems - lighting and cameras (W)	566
Tool cart (W)	803
D&C (W)	56
Avionics (W)	212.5
Propulsion (15 km/hr, 20 deg slope) (W)	11344
Total (W)	**13081.5**

Table VII-1: Hot Traverse Power Utilization

Hibernation Power	
GNC (W)	1.32
Crew systems - lighting and cameras (W)	0
Tool cart (W)	0
D&C (W)	0
Avionics (W)	5
Propulsion (W)	0
Total (W)	**6.32**

Table VII-2: Hibernation Power Utilization (Sans Heaters)

The nighttime heat deficit of the vehicle was assumed to be 204 W_{th}. The traverse time was estimated to be 80 minutes, the length of time required to traverse the vehicle operational range of 20 km at a constant speed of 15 km/hr. This is expected to be conservative; envisioning an emergency traverse back to a habitat or lander. The length of night was assumed to be 125 hours. Other assumptions were made as necessary, particularly in battery sizing which adds adjustments for depth-of-discharge, cycle life, calendar life, a 10% redundancy factor, parasitic mass factors for battery bank structure, and others.

R. Analysis Results

Analysis results for the seven cases examined are tabulated below. Listed for each case is the assumed nighttime heat deficit used in the analysis, the RHU thermal contribution, RTG thermal and electrical contribution, total battery energy required, the main energy driver for battery sizing (i.e. night survival vs. traverse), whether or not there is an energy surplus at night, and if so, an estimate for the continuous power that could be delivered assuming a 125 hour night. Further tabulated are estimates for battery volume, battery mass, the mass of the radioisotope power system added to the system, secondary mass increases due to power system integration, and a resulting mass improvement over the baseline case.

Case #	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6	Case 7
Case Description	Baseline	Balanced RHUs	Full RHUs	2-Module GPHS RHU	3 kW charge during traverse + full RHUs	MMRTG	½ size MMRTG[8]
Nighttime Heat Deficit	204 W_{th}						
RHU thermal (EOM)	N/A	70.8 W_{th}	204 W_{th}	451 W_{th}	204 W_{th}	N/A	N/A
RTG thermal (EOM)	N/A	N/A	N/A	N/A	N/A	1751 W_{th}[9]	875 W_{th}[10]
RTG electrical (EOM)	N/A	N/A	N/A	N/A	N/A	66 W_e[11]	33 W_e[12]
Battery Energy Required (EOM)	26.29 kWh	17.44 kWh	17.44 kWh	17.44 kWh	13.44 kWh	17.35 kWh	17.43 kWh
Energy Driver	Night Survival	Balanced	Traverse	Traverse	Traverse	Traverse	Traverse
Energy Surplus at Night?	No	No	Yes	Yes	Yes	Yes	Yes
Maximum Continuous Night-Ops Power[13]	None	0 W	133 W	133 W	101 W	199 W	166 W
Battery Volume	219 L	145 L	145 L	145 L	112 L	144 L	145 L
Battery Mass	354 kg	235 kg	235 kg	235 kg	181 kg	234 kg	234 kg
Power System Mass	N/A	3.44 kg[14]	9.84 kg[15]	6 kg	9.84 kg[15]	45 kg	23 kg
Secondary Mass Delta Estimate	0 kg	10 kg	15 kg	10 kg	50 kg (tracking solar array)	20 kg	15 kg
Mass Improvement Over Baseline	0 kg	105 kg	94 kg	103 kg	113 kg	55 kg	82 kg

Table VII-3: Radioisotope Integration Analysis Results

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[8] Assumptions for ½ size MMRTG take full-size MMRTG specifications and divide by two
[9] Based on 0.774% thermal output degradation per year calculated from MMRTG specification and 1892 W_{th} BOM thermal output [1]
[10] Assuming 0.774% thermal output degradation per year like larger MMRTG and 946 W_{th} BOM thermal output
[11] Based on listed MMRTG 4.8% power degradation per year and 108 W_e BOM power [1]
[12] Assuming 4.8% power degradation per year and 54 W_e BOM power output
[13] Using 125 hr night length
[14] Assumes 0.83 W_{th} per RHU, 86 RHUs at 40 g per unit
[15] Assumes 0.83 W_{th} per RHU, 246 RHUs at 40 g per unit

An examination of the results yields a few interesting trends. The inclusion of radioisotope sources generally allows the vehicle to have an energy surplus at night while decreasing the expected vehicle mass by approximately 100 kg. A tipping point is reached once a certain amount of thermal energy is imparted via radioisotope sources and the required battery mass is driven by traverse requirements rather than night survival. Because the traverse examined is so short, the relatively low power production of electrically-generating sources (RTGs) cause a negligible drop in battery sizing. Instead, the main benefit of RTG power production is seen during the night, with both RTG options examined causing the vehicle to be power-positive in this regime.

A power-positive vehicle during lunar night is worthy enough to discuss separately. Previous analysis of the vehicle was at times limited to 85, 100, or 125 hours; all very limited times compared to the full 354-hour night seen at the equator. It was understood that during night, the vehicle would enter a hibernation mode and be immobile and unusable, saving every joule of battery energy for heater power. A power-positive vehicle at night opens up *substantial* possibilities. The vehicle would first and foremost no longer be limited to a 125-hour night survival; in fact, the vehicle could survive *any* length of night during its expected lifetime. Without the restriction on night survival length, the vehicle would no longer be constrained to operation at the lunar poles – the vehicle could survive the night at any point on the lunar surface. Not only could the vehicle survive and travel to any passable point on the moon, with enough thermal and electric power it could survive indefinitely in permanently-shadowed regions, making long-term PSR study feasible. Even with no electrical power generation, adding radioisotope systems to the LTV could easily free battery energy during night to perform some science, mapping, or other activities as long as their energy usage would not deplete the battery before the night ended.

Examining the cases for the most optimal result is difficult since each case has its own benefits and drawbacks. Case 5 is the most optimal from a mass perspective, but current discussions indicate that reliable charging during traverses would be difficult in general, but especially during crewed operations as speed-made-good would be an order of magnitude over what is expected from remote operation. Assuming charging is not an option, Case 4 strikes a particularly notable balance. The 2-GPHS module provides enough heat for survival but an amount much more manageable than an MMRTG. It is much more compact and centralized than RHUs which does have drawbacks when heating isolated components, but would require fewer structural elements to integrate to the vehicle than several hundred RHUs. While it does not produce electricity, the thermal output would likely allow for a significant energy surplus to be held in the battery at night, allowing for limited operations. Lastly, while not fully designed or fielded, it relies on existing and tested technology for heat production and requires much less radioactive material than a full or half-sized MMRTG.

S. Secondary Mass Effects

Primary mass effects due to the inclusion of any radioisotope power system are trivial to estimate since the value is simply the mass of the power system itself. Secondary mass effects, however, are more difficult to estimate since they represent subsequent impacts to the vehicle design.

For example, integrating an MMRTG to the vehicle may or may not require a pumped liquid cooling system to efficiently distribute heat when needed. Adding the MMRTG would require adding structural mass to support the unit, electronic controller mass, and likely cause heat rejection systems to grow in size as well. Other changes, like having the vehicle charge via solar energy during traverse, would likely necessitate some sun-tracking system on the solar array which may otherwise be rigidly mounted in the vehicle baseline. In general, the most prominent sources of mass growth are expected be structural mounting elements and thermal management components (radiators, thermal straps, isolation struts, et. cetera).

Because of the difficulty in estimating secondary mass, estimates for the analysis above were mainly informed by engineering judgement, historical spacecraft design, and general rule of thumb guidelines rather than detailed engineering analysis.

VIII. Conclusion

This paper should serve as a reference point on the current state of radioisotope thermal and power systems and their engineering applicability to the proposed LTV. Basics of radioactive decay as well as radioactive shielding were presented and a cross-section of existing and near-term radioisotope systems was examined. Compounds with high alpha decay and low beta/gamma decay (such as $Pu^{238}O_2$) are preferable for use in the LTV due to the relative ease of shielding crew members and instrumentation from alpha particles. High beta-emitters like Sr^{90} are available in much higher quantities and lower costs than Pu^{238} but generally result in a mass penalty due to the additional shielding needed for crew safety and less thermal output per unit mass of material.

An analysis was performed that estimated the required battery energy and mass when using various radioisotope power systems. This analysis revealed that non-power-generating systems (radioisotope heating units or derivatives thereof) trended better in regards to mass savings as they can eliminate the need to electrically power heaters during the lunar night. By not powering heaters, it is even possible to have a power surplus during night which would allow for some limited mobility or science operation as long as such operations would not deplete the battery by the end of night.

In contrast, power-generating systems (RTGs and by extension future dynamic systems) have the same thermal benefits as radioisotope heating units but the added benefit of constant power production. This constant power production would allow for an increase in wattage available to payloads, scientific instruments, or mobility during night operations (up to ≈300 W depending on the exact system used). This additional power contribution comes at the cost of mass. The RHU options examined saved approximately 100 kg of vehicle mass, while the RTG options examined saved 50-80 kg.

The most mass-saving option analyzed is to design the vehicle to charge while performing traverses in conjunction with adding RHUs to the design. After a certain amount of radioactive material replaces heater power need, nighttime survival no longer drives the LTV battery sizing. Instead, the demands of traverse do, and minimizing these demands provides further mass-savings to the design. Charging during traverse is examined here since it does not require an in-depth examination of mobility energy usage, but reducing any power usage during traverses would result in battery mass reduction.

In all scenarios examined, the addition of radioisotope power sources (whether thermal or electric) resulted in vehicular mass savings. These power systems - while costly, hard to source, and difficult to integrate – have very special properties that make them uniquely suited for the environment of a lunar night. They degrade slowly and predictably, provide consistent power no matter their environment, and have been flight proven many times. However, one potential benefit may stand above them all: radioisotope power systems may unlock indefinite night survival for a lunar vehicle. With proper inclusion of RPSs, the proposed LTV may not need to be limited to use on the lunar poles – it could truly be a "go anywhere" vehicle and complete equatorial missions where the lunar night is two weeks long. Furthermore, an RTG-enhanced vehicle can conceivably produce enough power to remain mobile and perform continued science indefinitely in permanently shadowed regions.

It is precisely due to potential benefits like these that RPS options for LTV use should be considered closely. In general, the technical benefits to radioisotope power systems outweigh the technical drawbacks. Remaining drawbacks tend to appear at the program level and are not fully explored in this document. Because of this, no formal recommendation for the use of RPS technology in the proposed LTV will be given. Instead, the position of the authors and LTV reference design personnel is that a variety of existing and near-term radioisotope power systems meet and exceed the "minimally feasible" criteria needed for continued project evaluation.

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