

Potential Applications for Radioisotope Power Systems in Support of Human Exploration Missions

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Abstract. Radioisotope power systems (RPS) for space applications have powered over 27 U.S. space systems, starting with Transit 4A and 4B in 1961, and more recently with the successful landing of the Mars Science Laboratory rover Curiosity in August 2012. RPS enable missions with destinations far from the Sun with faint solar flux, on planetary surfaces with dense or dusty atmospheres, and at places with long eclipse periods where solar array sizes and energy storage mass become impractical. RPS could also provide an enabling capability in support of human exploration activities. It is envisioned that with the higher power needs of most human mission concepts, a high efficiency thermal-to-electric technology would be required such as the Advanced Stirling Radioisotope generator (ASRG). The ASRG should be capable of a four-fold improvement in efficiency over traditional thermoelectric RPS. While it may be impractical to use RPS as a main power source, many other applications could be considered, such as crewed pressurized rovers, in-situ resource production of propellants, back-up habitat power, drilling, any mobile or remote activity from the main base habitat, etc. This paper will identify potential applications and provide concepts that could be a practical extension of the current ASRG design in providing for robust and flexible use of RPS on human exploration missions.

Keywords: Radioisotope, Stirling, photovoltaics, Mars.

INTRODUCTION

Human exploration missions would most likely require a main power system in the 10's of kilowatts or higher depending on the extent of crew stay time and surface assets to support all activities. This power level is not sustainable with solely a radioisotope power source and clearly requires alternatives such as nuclear fission or large solar power/energy storage systems. However, radioisotope systems could have role in supporting surface operations. Radioisotope systems do not need deployment and basically supply power once assembled. Therefore, a RPS can assist in the movement of other mobile equipment to set up such a base, including a nuclear or solar power system.

The authors propose a concept of a mobile platform or Radioisotope Power Utility Cart (RPUC) with the power system as its primary payload. The RPUC could be semi-autonomously controlled from Earth during a cargo mission or controlled from the base. Applications include supporting power for long-range, multi-day piloted rover traverses up to several hundred kilometers, remote drilling operations that can be relocated to different drill sites, and back-up or emergency power requirements wherever needed.

This paper will describe a concept design for this higher power system based on the current design of the General Purpose Heat Source (GPHS) two-module, 140 We ASRG and assess the benefits of utilizing a continuous power output radioisotope source in support of a human mission activities. The power range selected for investigation is 1 to 3 kWe. The lower 1 kWe value is the power output of an 18 module GPHS assembly used for the heritage

GPHS-RTG flown more recently on Pluto New Horizons, for example. The upper bound 3 kWe limit was chosen as the amount of radioisotope power output flown on the Galileo mission using three GPHS-RTGs.

SYSTEM DESCRIPTION

The GPHS has been the core element of modern RPS used for many deep space missions when there is a lack of adequate solar illumination to power solar cells. It is a Department of Energy (DOE) standardized thermal source that produces approximately 250 watts of thermal power at the beginning of life (BOL). Dimensions of a GPHS module are shown in Table 1. [1]

Isotope

Table 1. Step 2 GPHS Dimensions

Height	5.82 cm
Width	9.32 cm
Length	9.96 cm

Plutonium Dioxide (PuO_2) is the ceramic form of Pu-238 that is used as the fuel for the GPHS. PuO_2 is placed in four iridium capsules and surrounded by a graphite shell to form each GPHS module.

Pu-238 is attractive because most of its radioactive decay energy comes from an alpha emission and it has a long half-life (87.7 years). Relatively low amounts of neutron emission come from both spontaneous fission and (α , n) reactions, which result from the interactions of the high-energy alpha particles with low atomic mass materials. Specifically, the iridium capsule prevents the alpha particles from leaving the fuel pellet (and interact with the surrounding graphite) but interactions with both O_{17} and O_{18} in the PuO_2 mixture does produce some neutron flux. Production of Pu-238 is commonly done by neutron irradiation of neptunium-237 (Np-237) in a high-flux reactor. The product of this irradiation is Np-238 that decays (2.117 day half-life) via beta emission into Pu-238.

Design Overview

The concept builds on the familiar General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) layout and couples this to a pair of Stirling convertors. Modifications to the heat source assembly would include removing the Multi-Layer Insulation (MLI), thermoelectric convertors and radiator fins while adding solid insulation (for use on Mars surface) and a sodium-potassium (NaK) liquid metal flow loop surrounding the GPHS modules. The GPHS-RTG contains 18 GPHS modules (producing about 4500 watts of heat BOM) and has an overall diameter of 0.422 m and a length of 1.14 m with a mass of about 55.9 kg. The outer shell would be made of an aluminum alloy with four mid-span bosses. The housing would need to be larger in diameter due to the poorer performance of the solid insulation (vs. MLI) and the fluid tubes wrapped around the GPHS modules.

A sketch of the heat source conceptual layout is shown in Figure 1. Fixing each heat source assembly to 18 GPHS modules and then estimating losses and component efficiencies produces a total estimated DC power output to the bus slightly more than 1 kWe.

Heat loss through the insulation, structure, and piping is assumed to be 5% of the total heat generated with a fixed 1.5% heat loss assumed through the piping and structure. Heat would be taken from the heat source assembly via a flowing NaK loop and moved to the two Stirling convertors. It would be necessary to ensure that the primary loop NaK does not transition into a vapor and this would be accomplished by maintaining sufficient pressure in the system with an accumulator such that the operating pressure is below the vapor pressure of the NaK.

The NaK would be pumped around the hot side of the system with two series annular linear induction electromagnetic pumps (ALIPs). The series configuration shown in Figure 2 is possible because the ALIPs are open channel pumps with external coils that provide a magnetic field. The ALIPs have an assumed efficiency of 15%.

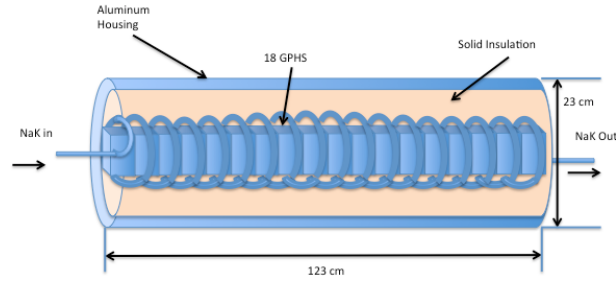


Figure 1. Conceptual Layout of Isotope Heat Source

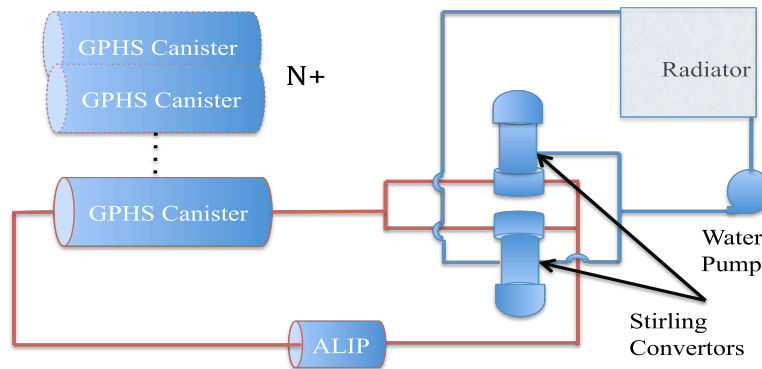


Figure 2. Stirling Isotope Power System Layout

It is important to note that the GPHS modules would not be exposed to the NaK and as such the potential venting / outgassing of the GPHS module cannot contaminate the NaK flow circuit. Since the structural loads would be relatively low, the materials in contact with the NaK working fluid could be fabricated from fully compatible materials such as stainless steel-316 (SS-316). In higher stressed areas this compatible material can be clad to the desired higher strength materials such as Ni-based superalloys.

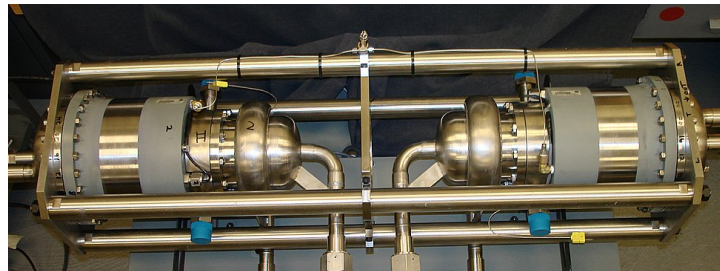


Figure 3. Sunpower's 2 kWe Dual Opposed Converter with Integrated NaK loop

For this study we used a well-defined 1-KWe Sunpower, Inc., converter as a reference point. This specific converter is of a very robust design developed initially for residential micro co-generation applications and operates at hot-end temperatures in the range of 775 to 825 K. All of the fundamental converter technology employed such as the linear alternator design, piston/displacer assembly, gas bearing system, etc., are exactly the same as those that would be employed in a high-power space-based design and are currently used in the ASRC converter. This converter has been modified to incorporate a pumped NaK hot-end heat exchanger, as shown in the image of Figure 3, operating at the NaK pumped loop test facility located at MSFC. The only change to the basic converter is the addition of the sheet metal (SS-316) inlet/outlet manifold that directs the NaK over the existing converter heater head. This same basic configuration would be employed in the alternative isotope-based system. Because of the

design goals for the basic convertor, the unit is heavier and has lower performance than desired for the proposed Mars system.

Building on this 2 kWe overall layout we then applied the higher hot-end material capabilities demonstrated as in the ASRG convertor. For the specific convertors considered, it was assumed that the Mar-M-247 material technology would be used. Because of potential interactions between this material and the NAK working fluid, it was assumed that a compatible material, such as SS-316, was clad to the NAK exposed surfaces. This cladding does not provide any structural support. Because of the high operating temperature capability of this material, it would be possible to retain conventional cycle temperature ratios but also provide higher rejection temperatures that greatly assist in the radiator sizing. Based on these scaling rules, a set of performance relationships were developed, which coupled the output power level and hot-end operating temperatures to the convertor efficiency. The specific power of the Stirling convertor itself improves somewhat with power level; however, this change is relatively small in comparison to the significant mass changes that occur in the convertor-related subsystems involving the multiple GPHS to convertor integration and waste heat radiator[2]. Therefore, the focus of the convertor evaluation was in the areas of integration with the GPHS heat source, vibration isolation options, and convertor impact on ALIPS configurations.

The most direct method of removing the waste heat from the Stirling convertor is to have a conductive coupling between the cooler section of the Stirling and a heat rejection surface. This method is used in the ASRG and consists of a cylindrical ring with the inner portion contacting the Stirling cooler and the outer surface of the ring in contact with the ASRG housing/radiator. The advantage of this configuration is obviously its simplicity. As the amount of heat rejected increases the trade between material thicknesses (and thus mass) an allowable temperature drop eventually favors other heat transport augmentation methods.

For this system a pumped loop heat transport system, water is passed over the Stirling cold end, transported out to the radiator panels, through the pumps, and returns to the Stirling convertor. Stirling convertors operate best when the inlet to exit coolant temperature difference is kept to a minimum. In general the temperature rise of a fluid used to remove the waste heat should be about 25 K or less (inlet to outlet of the Stirling) to ensure no Stirling cycle performance penalty. The radiator panel design consists of water heat pipes sandwiched between two outer face sheets is shown in Figure 4. Panel mass was approximately 3.5 kg/m² for the cases shown for the two-sided radiator. This areal mass does not include the fluid ducts, fluid, or pumps, which are accounted for separately. The pump design selected is scaled from other space pumps and is scaled both in efficiency and mass to meet the pressure drop and flow rate requirements of the system.

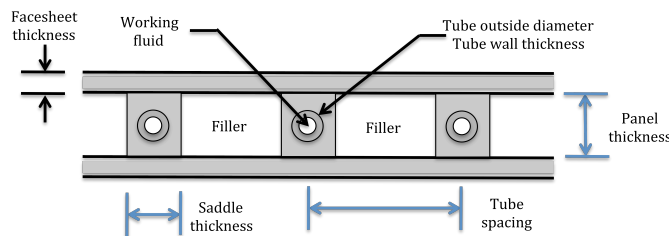


Figure 4. Radiator Panel Layout

SHIELDING

Because of both the gamma and neutron flux generated by the GPHS modules and the relatively close proximity of the astronauts to the power system some shielding would be required when prolonged stays near the isotope are needed. For this system the total dose from the power system was limited to 2.5 REM/year. Each year we assumed the astronauts would perform four 15-day trips per year and four 30-day trips per year in a rover that would be power by this system. To reduce mass, only shadow shielding is proposed, with the desire that the habitable portion of the rover would not receive direct radiation from the isotope assembly. Figure 5 shows some of the assumed

dimensions of both the shadow shield and where the dose plane is located. Tungsten would be used for the gamma shield and Lithium-hydride for the neutron shield.

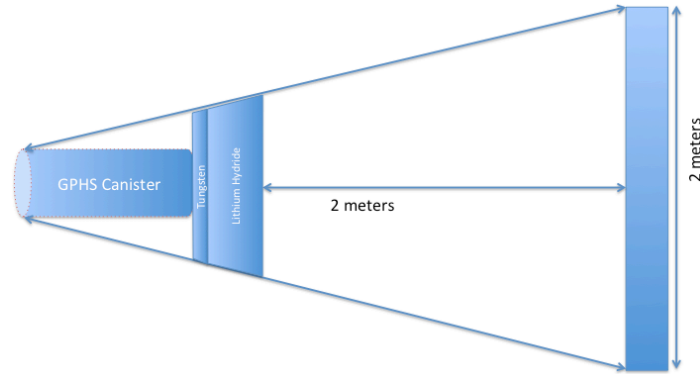


Figure 5. Shadow Shielding of the GPHS Canister

The summary for one 1.2 kWe system is displayed in Table 2. Some additional structure mass would be required to mount the radiator panels and attachment hardware to the cart deck to support the power system components.

Table 2. Summary of Stirling Isotope Power System

Number of GPHS Modules	18
Power Output	1.2 kWe
Specific Power	5.4 We/kg
Radiator Area	6.9 m ²
Stirling Convertors (2)	14.5 kg
Controller	23 kg
External Neutron Shield	14.5 kg
External Gamma Shield	47 kg
System Mass (w / no margin)	173 kg

MISSION ASSESSMENTS

The NASA Mars Design Reference Architecture 5 (DRA 5) was used as our human exploration mission framework from which to assess the RPUC potential applications. DRA 5.0 features a long ~500 day surface stay “split mission” using separate cargo and crewed Mars transfer vehicles with launches separated by 26 months. The pre-deployment of cargo poses unique challenges for set-up and emplacement of surface assets that results in the need for self or robotically deployed designs. For example, a fission power system or solar/energy storage main base system could be deployed with the power produced by the RPUC in providing mobility power for emplacement equipment and also power rovers, remote drills and backup power to the habitat. The concept here is to utilize the RPUC for as many applications as possible to expand its practicality. DRA 5 “Commuter” scenario includes a central habitat in addition to two pressurized piloted rovers. The central habitat would provide services to the full crew in between rover excursions, maintaining a minimum crew of two when both rovers are in the field. The rover sortie requirements were set at 100 km round trip distances accomplished in a two-week period. The rover application was used to evaluate, in part, what might be a useful power output for the RPUC in the 1-3 kWe range.

An option for providing power to the manned rover is to utilize a solar photovoltaic array / battery system (PV system). This system could be designed as an on-board system to provide the full power load to the rover or as a supplementary system working in conjunction with an ASRG power system. A likely rover operations scenario is one that has the rover traversing during the daytime one day (arrays stowed) and stationary during the following day recharging batteries while astronauts perform science investigations at that site. To evaluate the use of a hybrid PV / ASRG system three power system options were evaluated. The cases ranged from the PV system providing all of the power to the ASRG providing full power. The power requirements for the rover were estimated to be 3 kW

during the day and 2 kW at night, assuming a 2 kWe base load for rover housekeeping and life support for two astronauts, and 1 kWe of average drive power. These cases are given in Table 3.

PV ARRAY SYSTEM SIZING

Table 3. Hybrid PV / ASRG Power System Options

Case	PV System		ASRG	
	Day	Night	Day	Night
1	3 kW	2 kW	0 kW	0 kW
2	2 kW	1 kW	1 kW	1 kW
3	1 kW	0 kW	2 kW	2 kW
4	0 kW	0 kW	3 kW	3 kW

The PV system sizing would be heavily dependent on its operational environment. Items such as the time of year, latitude and array orientation significantly affect its output power to. For each of the cases listed in Table 3 the required array size was calculated at the four key Martian dates through the year (Vernal Equinox, Summer Solstice, Autumnal Equinox and Winter Solstice) and through array inclinations ranging from horizontal (0°) to vertical (90°). This sizing was done for latitudes of 0° to 30° North. It was assumed that the array was south facing and fixed at a given inclination angle. For each combination of the variables listed above, the array was sized to provide enough power to meet both the day and night power requirements specified for each of the cases. This was accomplished through an energy balance between the energy collected by the array during the day and the energy stored in the battery for use at night. The optical depth of the atmosphere as well as the efficiency of the photovoltaic cells affected the array output power. Diffuse light was also considered in calculating the array output. It was assumed that no applicable dust coverage was allowed to accumulate on the array surface. Since the vehicle was manned it would be reasonable to assume that the array surface could be cleaned of dust if necessary. The power system assumptions used to size the array is given in Table 4.

Table 4. Variables Used to Size the Solar Array

Variable	Value
Latitude	0°, 10°, 20° and 30°
Date	0 (Vernal Equinox), 172 (Summer Solstice), 344 (Autumnal Equinox), 515 (Winter Solstice)
Solar Cell Efficiency	26%
Optical Depth	1.5
Battery Charge/Discharge Efficiency	85% / 85%

The Mars environment was also a significant factor in the array sizing. The eccentricity of Mars's orbit causes the solar intensity to vary throughout the year. This variation ranges from approximately 493 W/m² near the summer solstice to 716 W/m² near the winter solstice. This 31% change in solar intensity has a significant affect on the array sizing and tends to level out the array sizing between the summer (where the sun angles are higher) and winter (where the solar intensity is greater).

Case 1: (3 kW Day / 2 kW Night) Results

For the first case the total day and night power for the rover is being supplied by the PV system. The results plotted in Figure 6 represent the required array area needed through out the year to meet the 3 kW day / 2 kW night power requirement. The array angle that provided the smallest array size was used for each latitude time of year combination. As the latitude increases the maximum array size shifts from the summer to the winter. This is because at latitudes near the equator the solar intensity (which increases from summer to winter) is more of a factor, whereas at higher latitudes the sun angle (which decreases from summer to winter) has a greater affect on the output power. The corresponding energy storage requirements for full day-night operation are shown in Figure 7.

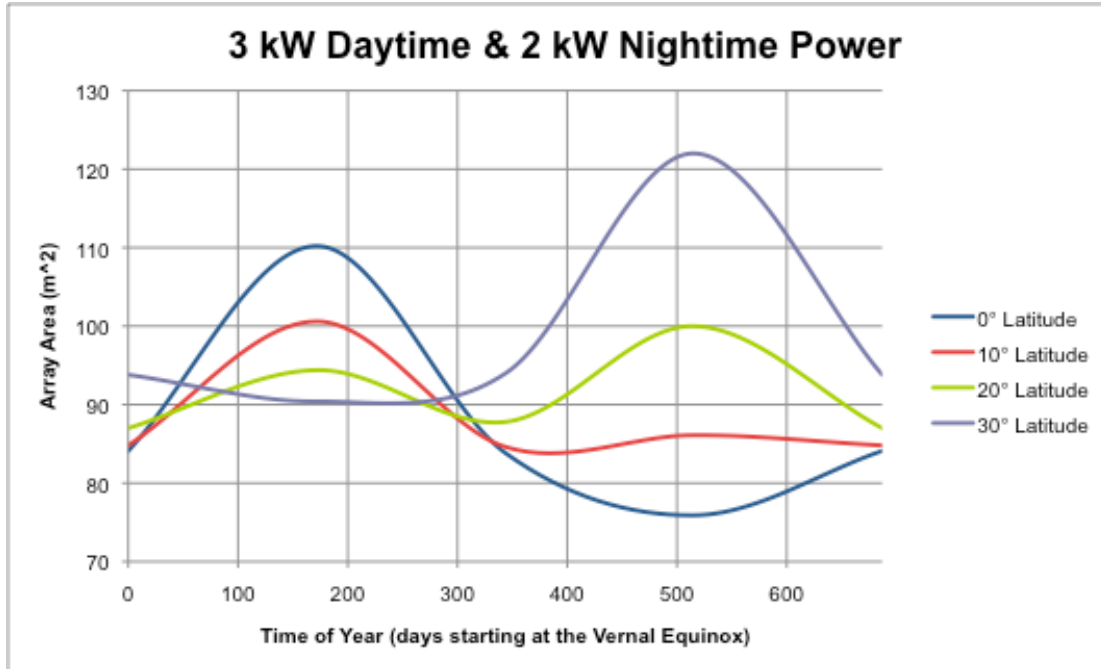


Figure 6. Case 1, Required Array Area Throughout the Year

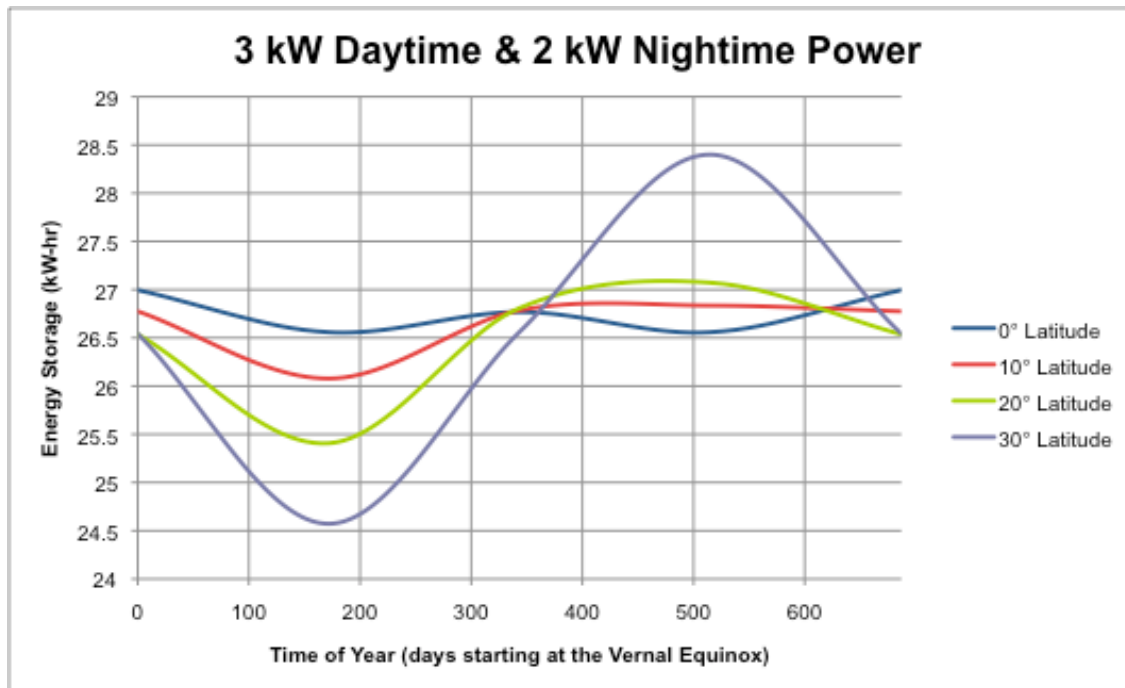


Figure 7. Case 1, Required Energy Storage for Different Latitudes Throughout the Year

From Figure 7 it can be seen that operating at higher latitudes has a significant affect on the required energy storage. This is due to the change in day length associated with operating at higher latitudes.

Case 2: (2 kW Day / 1 kW Night) Results

The second case is similar to Case 1 with both the day and nighttime power of 1 kW supplied by RPS. The results for Case 2, shown in Figures 8 and 9, are similar to Case 1 except that the array areas and energy storage capacity are reduced. The 1 kW reduction in day and night PV power resulted in a 43% decrease in the array size between Cases 1 and 2.

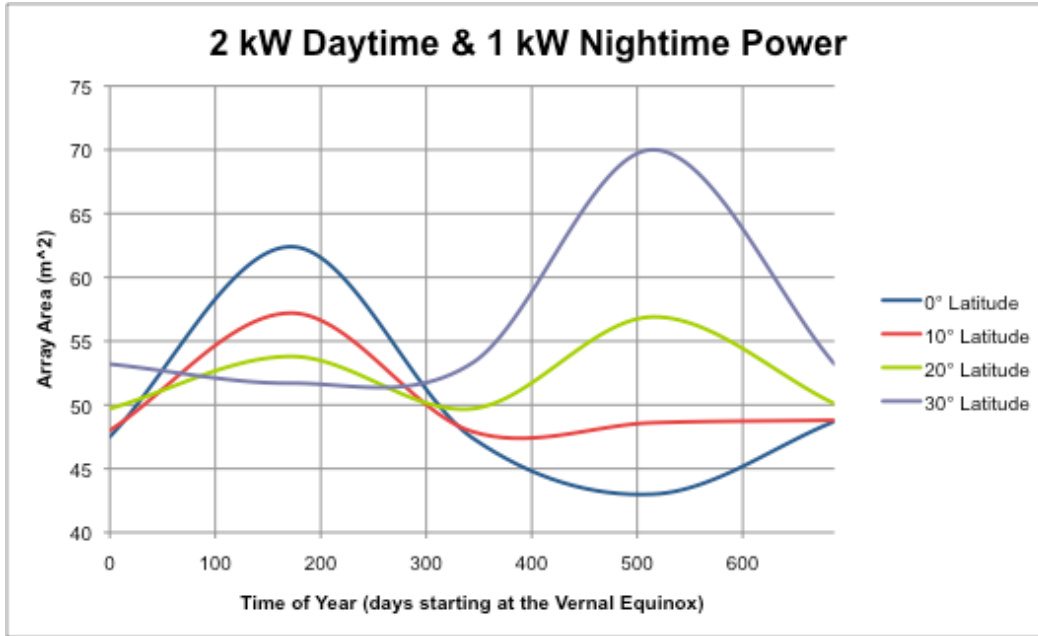


Figure 8. Case 2, Required Array Area Throughout the Year

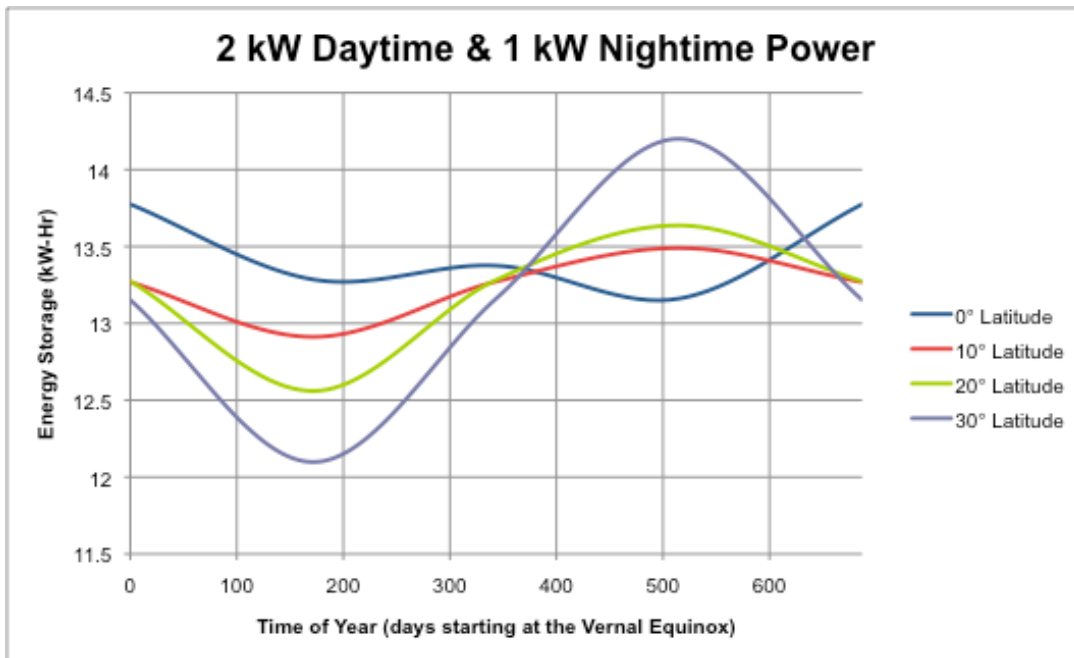


Figure 9. Case 2, Required Energy Storage for Different Latitudes Throughout the Year

Case 3: (1 kW Day / 0 kW Night) Results

Case 3 shows the effect of 2 kWe of RPS supplied power. Even though there was no nighttime power requirement for the PV system, energy storage would still be required. It was assumed that the daytime power requirement was needed from sunrise to sunset. Therefore to provide this power during morning and evening, when the sun angles are low, energy storage was utilized. Eliminating the need for nighttime power from the PV system significantly changes the array size requirements, as shown in Figure 10. Not only is the array size significantly reduced as compared to Cases 1 and 2, but also the minimum array size occurs during the winter for all latitudes when the solar intensity is greatest. The array sized would be reduced on average by approximately 80% compared to Case 1 and 66% compared to Case 2. The required energy storage capacity to meet the daytime output power of 1 kWe, from dawn until dusk, is shown in Figure 11. For this case the energy storage required curves are opposite those for Cases 1 and 2. For Case 3 the maximum storage requirement was during the summer and the minimum occurred in winter. Because there was no nighttime power requirement the day length was not a factor, and the shorter daytime period in the winter minimized the energy storage requirement.

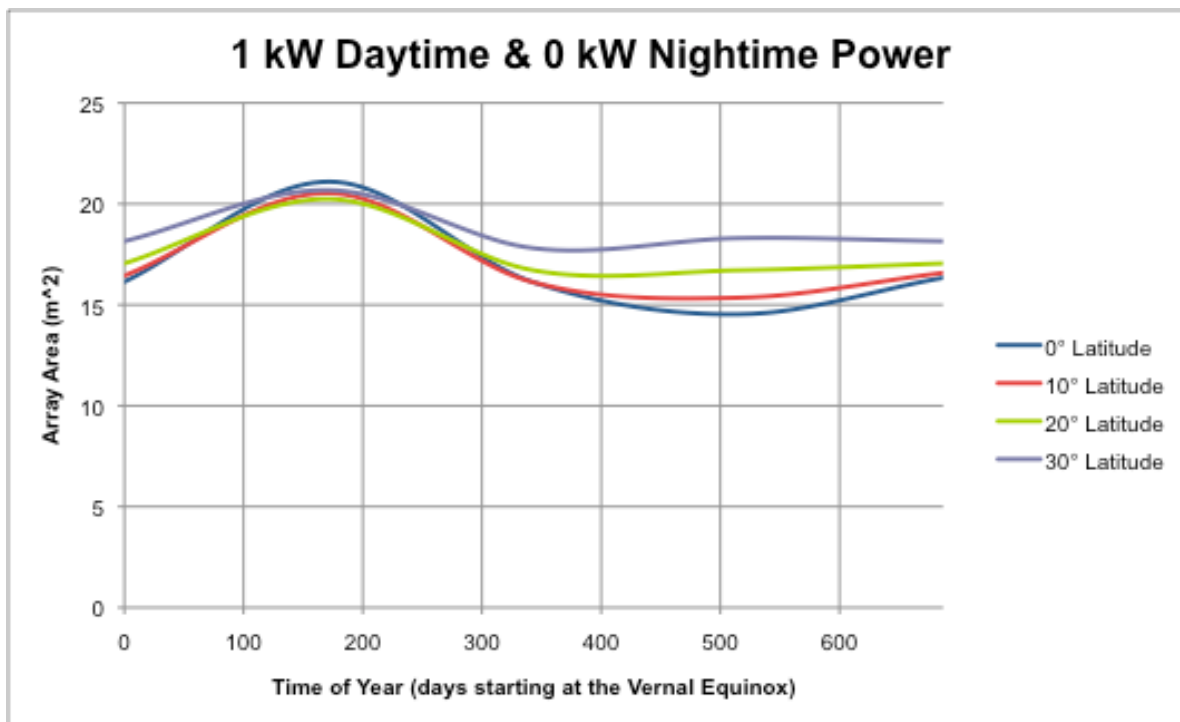


Figure 10. Case 3, Required Array Area Throughout the Year

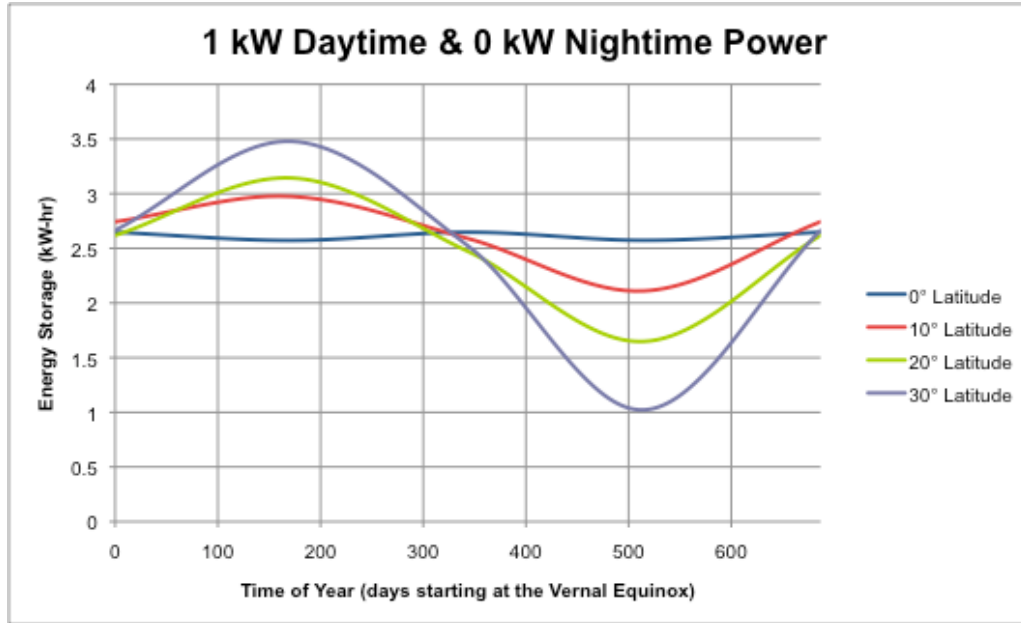


Figure 11. Case 3, Required Energy Storage for Different Latitudes Throughout the Year

Case 4: All RPUC, No Solar Array

The RPUC only option would also require some amount of battery for peak loads. Depending on the piloted rover's mass, drive speed, soil characteristics and slopes encountered during a traverse excess power would likely be required over the RPUC's output as with the PV hybrid option. However estimated nighttime 2 kWe load could be entirely supplied by the RPUC thus reducing energy storage mass. In addition heat from the RPUC could also reduce heater load requirements by utilizing the waste heat from the Stirling cycle. Possibly over half of the thermal power of the radioisotope could be used to provide heat. This could provide an advantage if the main base power source utilizes solar array/battery technology. This advantage could become quite significant if a major dust storm prevails causing reduced solar flux at the surface combined with reduced temperatures.

PV SYSTEM MASS

Using the array sizing shown in Figures 6, 8 and 10 the PV system mass can be estimated for an energy storage specific mass of 75 W-Hr/kg for a Li-ion battery [4] and an array aerial mass of 2.4 kg/m² [5]. For yearlong operation, which corresponds to the largest array area for each latitude for the three cases, the PV system mass is shown in Figure 12. As would be expected the mass drops off considerably from Case 1 to 3 as the PV system output power decreases. Operation around 10° N latitude provides the minimum PV system mass for Cases 1 and 2 where the minimum mass for case 3 occurs at 0° latitude.

To reduce the PV system mass the vehicle can be operated only at times of the year that require the minimum array and battery energy storage. These times correspond to the minimum array area shown in Figures 6, 8 and 10. The PV system mass for operating at these times is shown in Figure 13. This significantly limits the operational flexibility of the rover and is shown mainly as the lower bound on the PV system mass. Figures 9 and 10 represent an estimate of the upper and lower PV system mass for the three power requirement cases identified. Depending on the actual operating duration selected, the PV system mass will fall between these two limits.

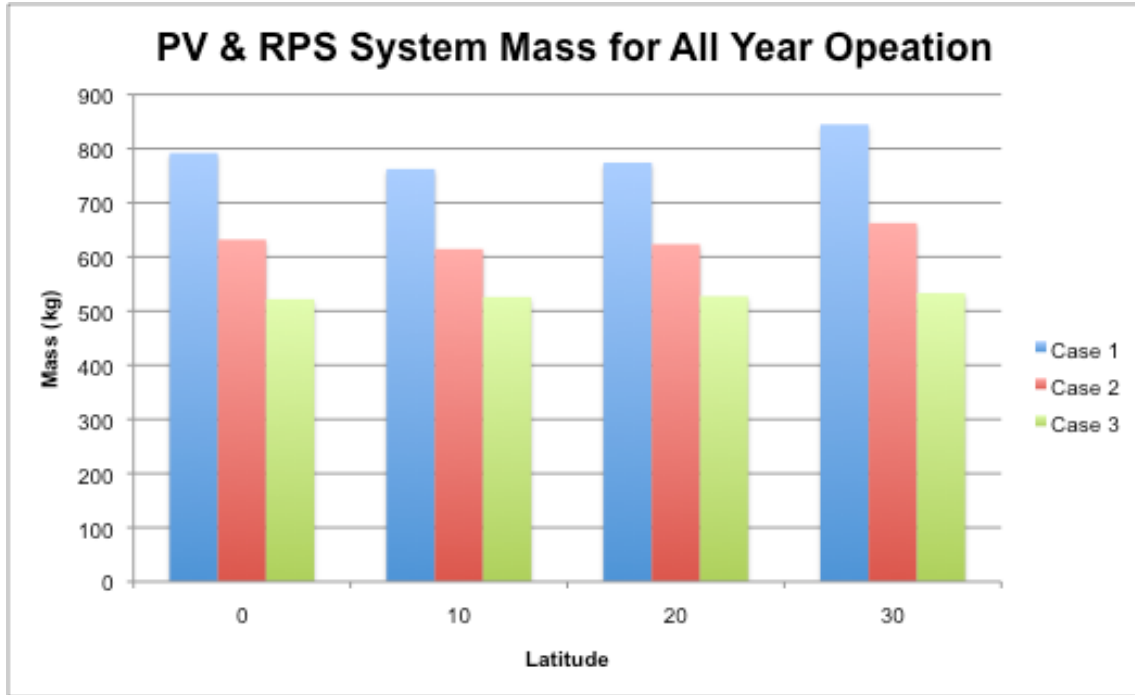


Figure 12. PV/RPS System Mass for Year Long Operation

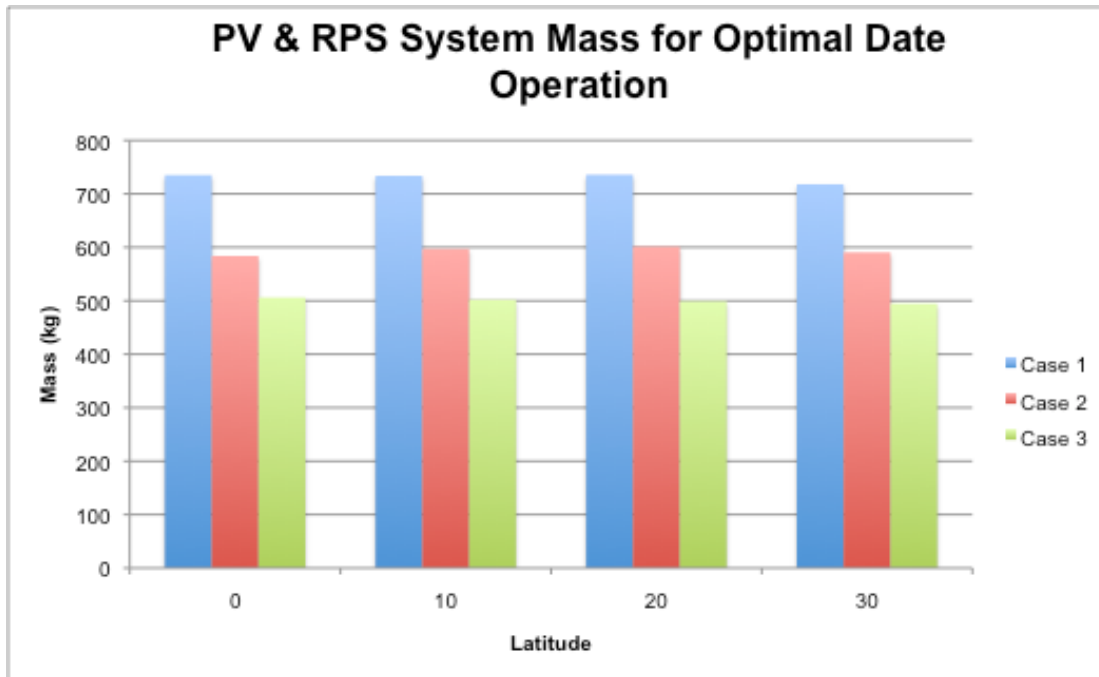


Figure 13. PV/RPS System Operation for Minimum Mass Operation

Masses for the 2 kWe and 3 kWe RPS systems are scaled linearly except for the shielding mass as shown in Table 2. The shielding mass is increased by approximately 30% and 60% for the 2 kWe and 3 kWe systems, respectively. This maintains the 2.5 Rem/yr dose rate and the shadow shielding configuration depicted in Figure 5. The combined PV/RPS system masses are shown in Figures 12 and 13.

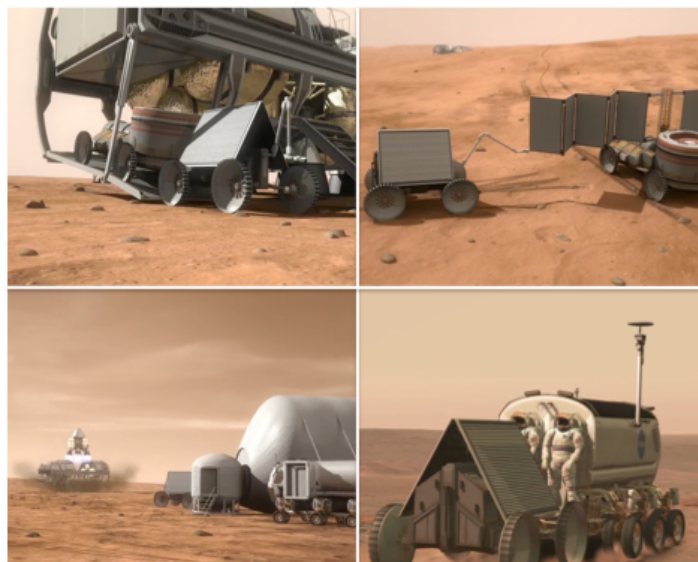


Figure 14. Clockwise from upper left: a) RPUC lowered off cargo lander with fission power system, b) remote deployment of power system, c) piloted rover traverse, d) auxiliary power at the habitat. Artist credit, Bob Sauls, Jack Frassanito and Associates.

CONCLUSION

The RPUC could compliment a human exploration mission in many ways. In our concept, the RPUC would be the first deployed equipment on the surface of Mars and function as the initial power source to set up the main power system and deploy other base systems such as the habitat, as depicted in Figure 14. The RPUC's robust, continuous and constant power capability would afford a high degree of flexibility, whether providing a reasonable solution to long-range traverses, habitat emergency augmentation power, or dust storm resilient power. The long half-life radioisotope fuel could service multiple human missions over decades, thus being a highly cost effective power approach.

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