Comparison of Power System Options Between Future Lunar and Mars Missions

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Abstract. Over the next decades NASA's space exploration efforts will follow the guidelines set out in the Vision for Space Exploration, which identified robotic and human exploration of the Moon and Mars as key objectives. NASA's Mars Exploration Program planned a number of orbiter and in-situ robotic science missions over the next decade, followed by human precursor mission in the second and by human missions in the third. The Lunar Exploration Program is expected to follow a similar exploration sequence, but would reach the human exploration stage earlier. Both lunar and Mars missions will scale up from smaller robotic science to large human exploration missions, with the possibility that lunar human exploration missions would act as Mars precursors. Similarly, the power systems enabling all of these missions have many commonalities. This paper discusses the power requirements and options for prospective lunar missions and their commonalities with similar class Mars missions. The main focus of the assessment will be placed on Radioisotope Power Systems (RPS), namely on Multi-Mission Radioisotope Thermoelectric Generators (MMRTG), Stirling Radioisotope Generators (SRG) and advanced RPSs. However, the power trade space will be complemented by additional power options, such as solar power generation and surface based small fission reactors, with an inclusion of batteries and fuel cells for power storage.

INTRODUCTION

The Vision for Space Exploration (The White House, 2004) identified a number of pathways for the US space program. Two of these paths were represented by a number of Mars and Lunar missions, both leading towards human exploration missions. Since introducing this vision, NASA has been working on the definition of these goals. Over the past year, NASA's Advanced Programs and Integration Office (APIO) was mandated to establish Strategic Roadmap (SRM) and Capability Roadmap (CRM) teams in order to identify mission priorities, decision points and technology development areas. The SRM and CRM team activities were completed in May 2005. At the same time Dr. Griffin, the Administrator of NASA, initiated a 60-day study to explore options that could enable the Vision. The findings from these studies are slowly emerging and at the time of writing this paper only partial information and general directions are available for discussion. While certain themes for future Lunar and Mars exploration can be anticipated, recommendations for the specific implementation and timeline for them can and likely will change in the near future. Consequently, in this paper various power source options are introduced, then their applicability for a number of Mars and Lunar mission classes are identified.

POWER SYSTEM CATEGORIES

Space power technologies can be categorized into two main groups, based on the power source. In one category the power generation depends on external power sources, such as on solar power or by the use of power beaming. In the second category power is generated by internal power sources. These sources include nuclear fission power and radioisotopes. With internal source first heat is generated, which in turn is converted into electric power. A summary of these power source categories is shown in Figure 1. The various power system technologies are briefly discussed below, with a specific focus on Radioisotope Power System. Chemical and solar power technologies are well established and their performance characteristics are readily available from open literature. Therefore, for these technologies only short summaries are given. Power beaming is also mentioned for completeness.

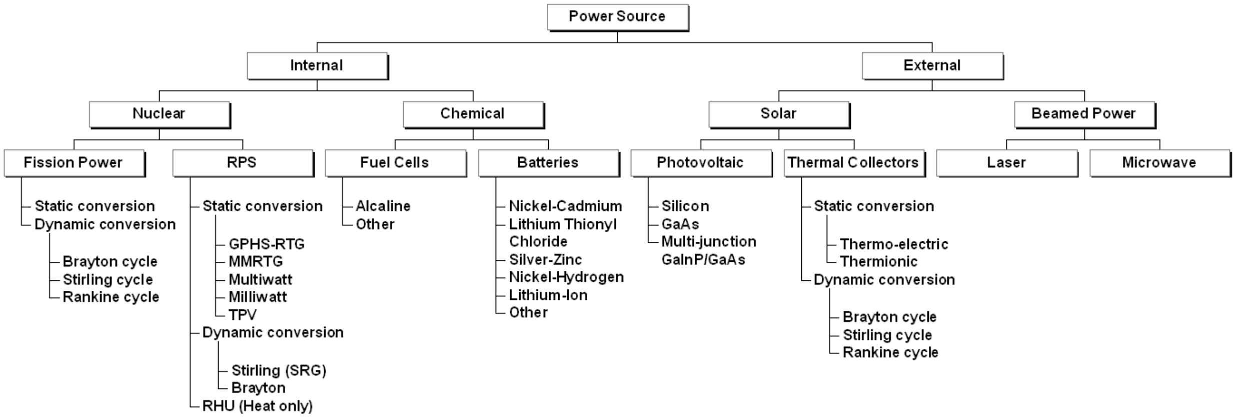

FIGURE 1. Categorization of Power Sources.

Nuclear Power Generation

In this section, Radioisotope Power Systems (RPS) are discussed, with a brief mention of fission power.

At present, NASA is developing two Radioisotope Power Systems, namely the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) and the Stirling Radioisotope Generator (SRG), both are designed generate about 110W(e) at the beginning of life (BOL). Concepts of these two systems are shown in Figure 2, while a projected performance summary is provided in Table 1. From these, the MMRTG was selected for the 2009 Mars Science Laboratory rover mission. It uses 8 General Purpose Heat Source (GPHS) modules with static power conversion. MMRTSs are capitalizing on 30 years of flight heritage from previous missions, such as from Voyager (MHW-RTG; 150 W(e)); Viking 1 & 2, Pioneer 11 (SNAP-19; 40 W(e)); Galileo, Cassini-Huygens, and Ulysses (GPHS-RTG; 285 W(e)); and Apollo 12/ 14/ 15/ 16/ 17 (Apollo Lunar Surface Experiment Package-ALSEP; ~70 W(e)). Upgraded MMRTG designs are under consideration with higher power conversion efficiencies (from today's ~5.5-6.5% to ~8-10% within 10 years), which are addressed by improved or new thermoelectrics. An SRG uses 2 GPHS modules and dynamic power conversion. The next step in SRG development includes the completion of an engineering unit by 2010 or 2012. Although the SRG-110 power system was not selected for MSL, the Stirling community is hopeful that future Moon missions may provide a proofing ground for this technology. Stirling Radioisotope Generators offer a few distinct advantages over static converter based systems. SRGs have a significantly higher conversion efficiency, in the range of today's ~22% to the next generation ~32%. For the present system the conversion efficiency is about 4 times higher than that of the thermoelectric conversion. Consequently, for the same power output SRGs require about 75% less Plutonium-238 (Pu^{238}) fuel. Because of its lower mass, the specific power of an SRG-110 unit is about 3.3 W/kg, compared to 2.9 W/kg for the MMRTG. Both of these stated specific power values are lower than the ~5.2 W/kg of the General Purpose Heat Source (GPHS)-RTG, however, the new designs are multi-mission capable. That is, they can operate both in atmospheres and in vacuum, while the GPHS-RTG is limited to in-space operation only. Advanced MMRTGs are targeting specific powers of 5W/kg and above. In short, SRGs are more efficient; require less Plutonium; and lighter. The lower Pu^{238} requirement also results in 75% less heat generation, which may simplify cruise-phase thermal designs for missions where a lander is encapsulated in an aeroshell until the completion of EDL. The lower fuel requirement (1 kg vs. 4 kg for the MMRTG) could significantly reduce the fuel cost per unit, by as much as ~\$6M based on an assumed fuel cost of \$2000 per gram of Pu^{238} (Surampudi, 2001). Beside these advantages, SRGs also have both real and perceived limitations. Stirling Radioisotope Generators are not yet space qualified. Lifetime for these dynamic converters is not yet proven, especially when considering outer planets missions lasting for up to 10-20 years. The SRG g-load tolerance requirement is currently 30g, compared to 40g for the MMRTGs. This is suitable to tolerate the launch environment, but limits landing to soft landing configurations only. Controller electronics are rather sensitive to radiation environments – such as at Jupiter – and controller radiation shielding could significantly increase the total unit mass. In case of failing one of the two Stirling converters, the whole unit could become unbalanced, resulting in the failure of the other half. Furthermore, EMI radiation could interfere with sensitive science measurements. EMI shielding could somewhat mitigate this effect, but that again would add mass to the system and would add complexity to the design. Finally, it is required to provide redundancy for these dynamic power systems. This means that each SRG enabled mission must carry a redundant unit, which lessens the power system mass gains against other RPS configurations. While these two power systems are still under development, the first New Frontiers mission – the New Horizons Pluto-Kuiper Belt mission, with a planned launch date of 01/11/2006 – will utilize a single General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG), with 18 GPHS modules and generating ~285 W(e) at BOL. After this mission NASA/DoE could assemble one more GPHS-RTG unit from currently existing parts, then this model is planned to be phased out. It was found that restarting GPHS-RTG manufacturing would be overly expensive, thus the idea was not pursued further. Future RPS developments could also include small-RPSs (Abelson et al., 2004a) (Balint, 2005) providing 10s to 100s of milliwatts or 10s of watts. The former would use multiple Radioisotope Heater Units (RHU: 1 Wt each), while the latter would use a GPHS module. Both configurations would utilize thermoelectric power conversion. Mission concept examples for Mars exploration, enabled by small-RPSs, are given in (Balint & Jordan, 2004) and (Balint, 2004).

Following the initial notion to develop a 100-200 kW(e) in-space fission reactor, NASA is currently in the process of refocusing this development effort towards smaller surface reactors. These reactors could scale in size from supporting In-Situ Resource Utilization (ISRU) based technology missions to a human lunar base. Exact configuration of these reactors are still under consideration, but it has been estimated that ISRU missions would require up to 30-50 kW(e) of power, while human bases would need up to 100 kW(e) or more.

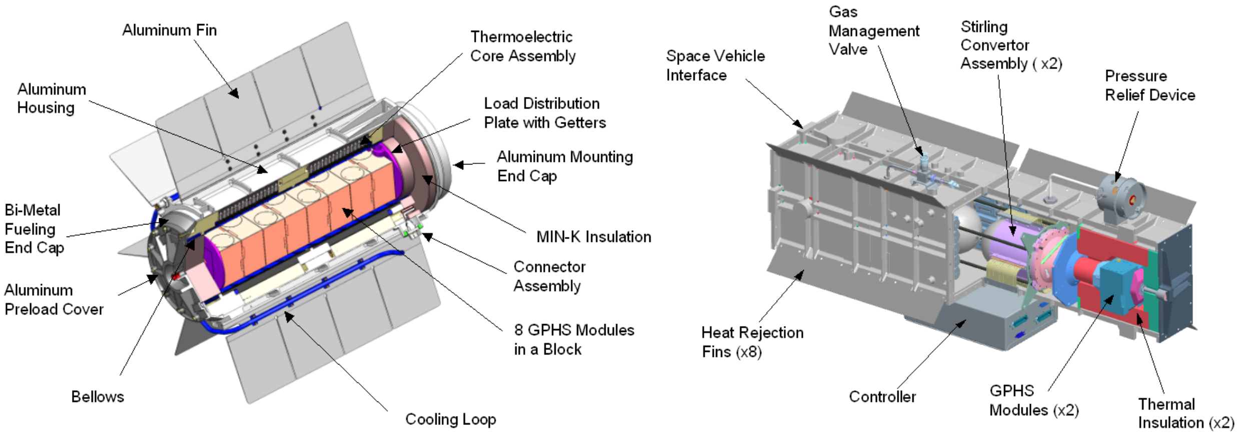

FIGURE 2. RPS Concepts Under Development, MMRTG and SRG.

Table 1. Performance summary predictions for 4 RPS designs. Two of them are currently under development by NASA/DoE with industry partners (MMRTG & SRG); one is suggested for future missions (upgraded MMRT); and one will be discontinued after the launch of the first New Frontiers mission in 2006. The upgraded MMRTG was conceived as a modified standard MMRTG, where the existing PbTe/TAGS thermoelectrics would be replaced with higher efficiency scutterudite thermoelectrics.

Parameter	MMRTG	Upgraded MMRTG	SRG	GPHS-RTG
Power per Unit (BOM), W(e)	~125	~160	~116	~285
Mass per Unit, kg	44	40	34	56
# of GPHS Modules per Unit	8	8	2	18
Thermal Power, W(t)	2000	2000	500	4500
Specific Power, W(e)/kg	2.9	4.0	3.4	5.2
Conversion type	Static	Static	Dynamic	Static
Converter materials	PbTe/TAGS	Scutterudites	Stirling	SiGe
Technical Readiness level	TRL-5	TRL-3	TRL-3	TRL-9
Availability	MSL-2009	2014+	2012+	Discontinued

Chemical Power Generation

Batteries provide energy storage using internal chemical power. These scalable energy storage systems are highly reliable, but heavy, presenting a significant impact on the total system mass. To increase voltage or current, the units are connected in series or parallel, respectively. Battery life cycle is influenced by temperature; depth-of-discharge; rate of charge and discharge; and degree of overcharge. Primary batteries are not rechargeable and usually last for short durations, measured in hours. They are typically used on launch and entry/re-entry vehicles, and on planetary entry probes. Batteries provide well-regulated power, typically 28±5 V. Examples for these include Lithium-Thionyl Chloride ($Li\text{-}SOCl_2$) and Lithium-Carbon Monofluoride ($LiCF_x$) cells. The specific energy (at 0°C) for Lithium based primary batteries today is ~250 Wh/kg, which is expected to grow to ~400 Wh/kg in 5 years and to ~600 Wh/kg in 10 years. (At lower temperatures the performance degrades – e.g., by 3 to 5 fold at –80°C.) Secondary batteries are rechargeable, and are only used for energy storage. Examples include Lithium-Ion, Lithium Polymer Electrolyte, Lithium Solid-State Inorganic Electrolyte and advanced Lithium-Sulfur (Li-S) batteries. Secondary batteries are important during peak load operating modes, where the power requirement exceeds the power output from the main power source (e.g., from an RPS), or during eclipses or overnight operations. However, their performance is lower than those for primary batteries. For example, the specific energy (at 0°C) for the present state of practice is ~100 Wh/kg, which is expected to increase to 120 Wh/kg and 200 Wh/kg in 5 and 10 years from now. The battery lifetime is also expected to increase from today's 5 years to 10 and 15 years, respectively. Fuel cells can be used for human missions that require power in the multi-kilowatt range for up to ~10 days (e.g., on Space Shuttle flights). They have higher specific energy than batteries. Flywheels can be used as alternatives to secondary batteries. They are attractive for low-Earth orbiting missions, requiring reusable energy storage up to 5 kWh or more. Flywheels are not chemical power sources, but included here for completeness. Detailed discussion on primary and secondary batteries, on fuel cells, capacitors and flywheels are given in (Mondt et al., 2004)

Solar Power Generation

Solar power generation utilizes an external power source, the Sun, and converts its energy to electricity. Solar flux decreases with the inverse square of distance from the Sun, and in addition for Mars surface missions, with the presence of a Martian atmosphere and potential dust storms there. Latitude, seasonal and diurnal changes also play a role in solar availability and intensity. The solar constant (S) at the orbital distance of Earth from the Sun is 1367 W/m^2. Compared to that (100%), solar irradiance values are significantly lower at Mars, as measured in orbit (43%), on the surface under clear conditions (22%) and under cloudy conditions for local or global storms (13% to 6.5%) (Balint, 2004). Solar radiation can be converted into electric power using solar thermal collectors or photovoltaic (PV) arrays. These options are shown in Figure 1. Solar panel size and mass scales linearly with power. For example, a two-fold increase in power results in the same magnitude of increase in panel size and mass. Photovoltaic arrays employ solar cells for power conversion. Some of these include single crystal Silicon cells and single junction Gallium Arsenide cells, converting photons of near infrared energy to usable energy. Multi-junction or multi-layer solar cells, such as Gallium Indium Phosphide/Gallium Arsenide, use different spectrums of sunlight, hence increasing the conversion efficiency. Typical conversion efficiencies for these three types are: ~14.8-16.6% for Si; ~19-22% for GaAs; and ~22-26.8% for GaInP/GaAs (Cutts & Prusha, 2003). These panels also degrade at a rate of ~3.75%; 2.75% and 0.5%, respectively (Wertz & Larson, 1999). Important characteristics of solar cells include: high efficiency; good radiation, UV and atomic oxygen tolerance; long life; robustness for mechanical stress tolerance; high reliability and low cost. Similarly, the arrays can be characterized by their specific power; stowed volume; cost; and reliability. The main solar array categories include body mounted; rigid; and flexible or deployable configurations. Others include concentrator, electrostatically clean and high temperature arrays. The state of practice for body mounted array areal power is ~350 W/m^2. For rigid arrays the specific power is 30-60 W/kg, with a corresponding specific volume of 5-10 kW/m^3. For flexible or deployable arrays these are 40-80 W/kg and 10-15 kW/m^3, respectively, but the arrays may require complex deployment. Further information on this technology can be found in (Cutts & Prusha, 2003).

Beamed Power

Power beaming by microwave from space to Earth was first suggested in 1968. In the 1980's NASA extended the technology to laser based power beaming between space assets, then later from ground-to-space. Landis provided a numerical example for power beaming from Earth to the Moon. With a GaAs laser diode array, a lens diameter of 2 m, a distance of 4×10^8 m and assuming diffraction limited beam spread (accounting for atmospheric turbulence), he calculated the total spot radius at the Moon as 250 m with a corresponding illuminated area of 0.2 km^2. Using a 12 MW(e) power source at the sending end (e.g., on Earth), the received power at the Moon is ~50 kW(e), after all conversion and beaming losses are accounted for. This corresponds to a low end-to-end beaming efficiency of ~0.4% (Landis, 1992). Furthermore, collector arrays with a size of ~40 football fields would present severe logistical problems for landing, deployment and maintenance. Microwave and laser beaming technologies differ in many ways, including antenna configurations. However, beaming efficiencies and antenna size are similar between the two, hence the same conclusions apply. Therefore, it is concluded that power-beaming technologies require significant improvements (i.e., 2 orders of magnitude in conversion efficiency from ~0.4% to ~40%), before they can be seriously considered.

POTENTIAL LUNAR AND MARS MISSIONS

Pathways for Mars and Lunar exploration can be discussed from science or engineering points of view. The first could address the line of science enquiries and themes, while the second could describe the sequence of missions over a given time period. Pathways should also maintain analysis and instrument capabilities to allow for cross cutting paths for better program flexibility and response to discoveries. Mission concepts that can populate these various pathways reflect the recommendations of the National Academies (NRC, 2003) from a scientific point of view, while programmatic considerations are based on NASA's priorities and budget allocation. At present, NASA is performing an institution-wide planning activity to establish these pathways for all targets of interest, while reflecting the Vision for space exploration. Therefore, at this point only a generic list of potential missions can be assembled, without the relating pathways. These possible missions are summarized in Table 2, where the list for Mars exploration missions also includes some of the selected missions (e.g., MRO, Phoenix, MSL).

Table 2. Selected and Potential Missions for Mars and Lunar exploration, with an estimation of the mission class and power options.

Selected & Potential Missions	Class	Power Option(s)
Mars Exploration		
Orbiters (e.g., MRO)	Medium/Large	Solar (typical for Mars orbiters)
Phoenix	Scout	Solar selected
Mars Science Laboratory (MSL)	Large	RPS (MMRTG selected)
Deep Drill	Large	RPS (solar panel trades were also performed)
Mars Sample Return (MSR)	Flagship	Solar (RPS trades were also performed)
Astrobiology Field Lab (AFL) rover	Large	RPS (based on MSL heritage)
ISRU Testbed, Tech demo	Large	Solar (RPS trades were also performed)
Scout (small missions)	Scout	Solar (mission cost cap may limit RPS usage)
Large human precursor & manned	Flagship	To be determined (based on architecture / availability)
Lunar Exploration		
Lunar orbiters	~$400M	Solar
Small landers	~$400M	Solar (RPS: MMRTG or Stirling)
Human precursor - ISRU	Large/Flagship	RPS; Solar; or else (based on architecture)
Human mission (short stay)	Flagship	Battery; solar; fuel cells (e.g., Apollo architecture)
Human base	Flagship +	To be determined (based on architecture / availability)

POWER OPTIONS AND STRATEGIES FOR LUNAR MISSIONS

In this section various aspects of power system options and potential selection strategies are discussed in light of mission types. Comparisons between notional Moon and Mars missions will be used to highlight cross cutting themes for mission design approaches.

Launch Environments, Cruise and Landing

Preliminary mission designs generally focus on the feasibility of the science operations phase. Nevertheless, some of the earlier phases of the mission could also impact the design in order to accommodate the selected power systems. For example, RPSs must be integrated with the spacecraft on the launch pad prior to launch. (DoE oversees this operation.) Consequently, RPS enabled missions should be designed with easy accessibility to the spacecraft before launch. This could introduce an ever-increasing challenge with larger number of RPSs on human precursor or human missions. Since RPSs generate heat continuously, this excess heat must be removed through all mission phases (Balint & Emis, 2005). The ambient temperature environments and heat transfer mechanisms also vary throughout the mission phases. On Earth, during the storage and launch phases, the temperatures and pressures are terrestrial, where the mechanisms include convection, conduction and radiation. During the cruise phase in space, radiation is the dominant heat transfer mode, while conduction also plays a role. Cruise phase operations introduce differences between Moon and Mars surface missions. EDL (entry, descent and landing) on Mars utilizes an aeroshell for atmospheric entry. Therefore, during cruise phase the spacecraft is bottled up inside this areroshell. The heat generated by the RPS must be removed through an additional cooling system. A typical configuration would use a fluid loop and external radiators. This adds mass to the spacecraft and complexity to the mission. Since the Moon does not have an atmosphere, landing is performed through all propulsive means. Without and aeroshell the RPSs could radiate the waste heat directly to space during cruise and also during surface operations. In comparison, integration of other types of power systems, such as solar panels and batteries, do not represent integration challenges and thus will not be discussed further.

In-Orbit and Surface Operations

Both the Moon and Mars are relatively close to the Sun. At 1 AU or at 1.5 AU solar availability could point to the use of solar panels. Consequently, orbiter missions around the Moon and Mars historically used solar power generation, combined with secondary batteries to mitigate eclipses and other non-nominal operations. It is likely that lunar and Mars orbiters will continue to use solar panels for power generation. For example, the recently launched Mars Reconnaissance Orbiter uses solar panels, and the expected lunar orbiter with an anticipated mission cost of ~$400M will likely follow the same trend. However, solar power may not be suitable for all of the missions listed in Table 2. Seasonal changes at the polar regions of Mars could result in insufficient illumination that would shut down the mission for up to 6 months (Balint, 2004), and potentially could fail the spacecraft. Similarly, diurnal cycles on the Moon would have the same effect in 14-day intervals. On the Moon the desired landing location for prospecting and in-situ resource utilization would point to permanently shadowed craters at the poles. Therefore, the power source selection strategies should be discussed on location-by-location basis. The second lunar mission after the orbiter might be a small lander, with a similar ~$400M cost allocation. For this cost cap the mission would have a smaller scope than the proposed (but not selected) New Frontiers South Pole Aiken Basin Sample Return mission with a ~$700M cost cap. A short mission to the equatorial region of the Moon, with mission duration shorter than 14 days, could utilize solar panels or even batteries or fuel cells. A longer mission must address survival mitigation to avoid thermal death. The thermal environment could be maintained by resistance heating or through utilization of waste heat from RPSs or RHUs. Resistance heating would require secondary batteries, which would be charged during the 14-day sunlit period. In order to reduce power usage, the lander would switch to a low power mode for the alternate 14-day period, to reduce battery usage. For a static lander a typical high power mode is driven by telecommunications, either Direct-to-Earth or through a relay orbiter. For this cost cap an RPS (MMRTG or SRG) enabled mission might be also considered. In addition, a hybrid power system with three components would also be feasible, where during the 14-day sunlit period power would be provided by solar panels and RPSs, supplemented by batteries at peak power modes. During the 14-day low power mode the spacecraft would be supported by the RPSs, providing both electric power and heat. The Phoenix lander, targeting the high latitude regions of Mars, could provide some heritage to this type of lunar landers. Mobility platforms might include MER class rovers. Larger rovers would increase mass, volume, cost and operational complexity, which may point to lunar missions towards the second part of the next decade. Prospecting for in-situ resources would likely require landing in the permanently shadowed craters of the Moon. Detailed discussions on rover concepts, enabled by RPSs for both Mars and Moon missions are provided in (Abelson et al., 2004a) and (Randolph et al., 2005). For rovers, the main power drivers are traversing and telecommunications, in addition to some of the science modes for prospecting and in-situ analysis. RPS enabled rovers typically use a hybrid power system, where during peak power modes power is drawn from the RPS and the batteries, while during low power modes the batteries are recharged (Balint, 2005). In the opinion of this author, lunar missions with a cost cap of ~$400M would be limited to Phoenix class static landers or MER class rovers. These missions could use either solar power or an RPS, combined with secondary batteries. Human precursor and human missions, however, would require significantly higher power levels. Large scale prospecting in permanently shadowed craters would necessitate RPS enabled rovers, long mission durations, and significant traversing capabilities. The rovers should cover 10's of square kilometers to map the extent of the resources. Traversing capabilities at this scale would need MSL class rover configurations or possibly more. (MSL is designed with a single MMRTG.) If resources are found in the craters, ISRU demonstrators could offer an initial proofing for that technology. ISRU demonstrators on Mars were considering power requirements in the kilowatt range using solar panels. On the Moon ISRU would necessitate RPSs. Even a scaled back demonstrator might use multiple MMRTGs or SRGs, increasing the mission cost significantly. Large-scale ISRU missions, producing propellant, would call for higher power levels and continuous operation over long lifetimes. The process would also include a significant amount of regolith excavation, transfer and processing by larger rovers. Finally, the extracted resources would need transferring to lunar bases for further use. Human bases will likely target sunlit locations on the surface of the Moon. Therefore, transferring resources from ISRU bases to human habitats – even a few kilometers away – would introduce a challenge. Long duration human habitats on the Moon will likely use power in the ~50-100 kW(e) or higher range. These power levels cannot be provided on a continuous basis by existing power systems; therefore, this should be addressed through technology development of advanced power systems, which could include surface fission reactors. Building a lunar base could be envisioned in multiple phases. Landing of these assets in close proximity could benefit from a navigation network, made up by navigation beacons on the surface. Simple beacon designs can be envisioned as RHU based trickle charge devices with super capacitors, designed with high g-load tolerant housing for impact landing. G-load tolerance is also important for RPSs. Current designs (MMRTG, SRG) can only tolerate up to 40g, which would only allow for soft landing. Based on these considerations it can be concluded that sizing of the power systems for lunar missions are similar to those for the corresponding Mars missions, although the operating environments may differ greatly. These potential lunar missions could be enabled by current power system technologies up to human precursor missions.

CONCLUSIONS

The Robotic and Manned Lunar Exploration Programs are currently in a planning phase. The various missions discussed in this paper provide only a brief overview of the possible missions expected over the next decades, without an attempt to prioritize them. The main focus was placed on power system options and availabilities, aligned with the various missions. It was found that in some sense there are similarities between the power system options for Lunar and Mars exploration missions. However, there are also significant environmental differences that are unique to these two destinations. For orbiting spacecraft at both targets, historically, solar power generation was and is found to be the best suited option, due to simplicity; low mass; high reliability; and high power availability. Power source selection for lunar surface missions are influenced by the 14 day diurnal cycle and landing location. For short-stay lunar missions at the equatorial regions solar power generation could provide a preferred solution. (Under special circumstances even primary batteries could supply sufficient power for some missions.) In permanently shadowed craters at the Polar Regions of the Moon or during Martian winters RPSs could provide an advantage. Longer equatorial missions on the Moon could consider hybrid systems, with the combination of solar panels, and/or RPSs paired with secondary batteries. When RPS is required, lunar missions could offer a proofing ground for Stirling Radioisotope Generators, due to the shorter cruise and potentially short mission times. Both MMRTG and SRG are capable of operating in vacuum and in atmospheres. Therefore, they are applicable for both destinations. An upgraded MMRTG would be more enhancing than enabling for these missions, compared to standard RPSs. As the lunar program will move from robotic to long duration human exploration missions, the power requirements will increase significantly, from the few hundred watts to the 50-100 kW(e) range. Obviously, these latter missions cannot be supported by today's technologies and would likely require power systems beyond solar panels or RPSs. For the smaller missions, power drivers are considered to be mobility; telecommunications; and some of the science analysis instruments, such as GC/MS. For human precursor or human missions continuous high power generation is required to operate ISRU and habitats / life support systems. However, it is important to emphasize that looking at mission classes and power requirements alone cannot address the full extent of the trade space. For example, the lunar exploration pathway should address prospecting for in-situ resources and linking the findings to potential human missions. These resources on the Moon will likely be found at dark and permanently shadowed craters in unknown quantities. Mining and processing these resources will require significant regolith displacement, which might not be achievable with small rovers and power levels in the low hundreds of watts. Even if large volumes of resources could be found and processed in craters, linking that architecture to future lunar bases could be challenging and was found to be beyond the scope of this study.

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