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Radioisotope Power Systems to Enable Extended Lunar Science and In-Situ Resource Utilization Missions

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The Moon's surface environment offers a significant challenge for most space systems and, particularly, for power technologies. First, the Moon's rotational synodic period is 27.3 days long because it is tidally-locked with Earth and thus matches its orbital period. However, for a point on the lunar surface with respect to the Sun returning to the same position in the sky, called a synodic day, is 29.5 days or 708 hours. Therefore, a lunar day is 354 hours of sunlight and 354 hours of darkness. Equatorial diurnal temperatures range from about 400K at noon to 100K during the night. Within craters and permanently shadowed regions (PSRs) temperatures can be a constant 40K or below. Sunlight in the lunar polar regions can range from total darkness in deep polar craters and at higher elevations, potentially nearly continuous conditions are possible. However local topographical features such as outcrops or more distant mountains and ridges would obscure the Sun even in these extended sunlit areas and thus create intermittent shadowed periods depending on seasonally varying Sun angle and the obscuring topographical features. Thus, the power system technology that a mission selects becomes a critical trade.

I. INTRODUCTION

Surviving the long lunar night poses a significant challenge for photovoltaic arrays and energy storage systems. Providing the energy required for both nominal mission operations and possibly electric heaters to maintain "keep-alive" night time temperatures for electronics and other vital systems during the lunar night reduces the amount of payload otherwise available for science and exploration investigations. However, radioisotope power systems (RPS) produce power by converting the heat produced by natural isotopic decay into electricity. The plutonium-238 (Pu-238) fuel source offers high energy density along with an 88-year half-life. NASA has flown multiple versions of the Radioisotope Thermoelectric Generator (RTG) technology using Pu-238 for decades to distant planets and the planetary surfaces of the Moon and Mars. While the extreme range in lunar temperatures and long duration diurnal periods pose an extreme environment for conventional power system technology, RPS has proven their capability to operate for years in such conditions as shown by the NASA Apollo mission's Systems for Nuclear Auxiliary Power (SNAP) SNAP-27 RTG and more recently the Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) currently powering Curiosity rover.

An even greater challenge is a lunar polar mission to provide ground truth of specific locations, concentrations, depth, etc. of potential water ice and other volatile deposits as indicated from orbiting instruments. RPS technology is uniquely capable to provide the required electrical and thermal power for the multi-year exploration timelines likely required to fully perform such a mission. It is anticipated that significant amounts of heat will be required for rover mechanical subsystems and electronics. The constant heat produced from isotope decay can supply this heat thus reducing the electric power demands of electric heaters. Many processes for the extraction of volatiles from the regolith requires heat, therefore the waste heat available from the RPS reduces the electric power requirement. Advanced RPS systems using higher efficiency dynamic conversion technology can produce about four times the electric power of the conventional RTG from the equivalent quantity of radioisotope fuel. Several advanced technology concepts continue to be in development and their features will be discussed as well as current and future RTG concepts.

II. LUNAR ENVIRONMENT AND SOLAR POWER SYSTEM CONSIDERATIONS

The most recent accepted measurements of the Earth orbit total solar irradiance value are ~1,361 W/m^2. Since the Moon has no appreciable atmosphere, an array can be sized using this value. It is anticipated that a science mission would likely have a flat mounted, non-tracking array due to simplicity and cost. Figure 1 shows the solar irradiance that would reach a zenith pointing fixed non-tracking array at the lunar equator. The conseqence of a fixed array is increased area needed to provide the same total energy that a tracking array would provide. A trade-off can be made comparing the complexity, cost and risks between tracking and non-tracking solar array.

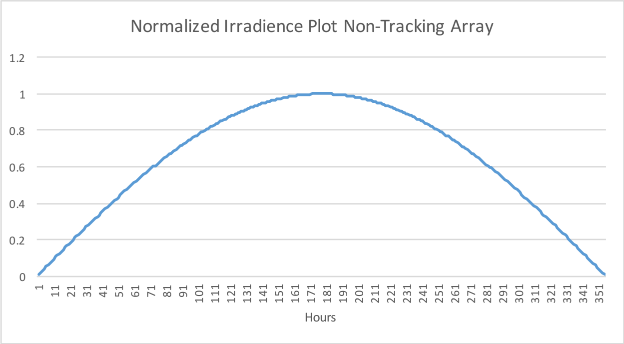

Fig. 1. Normalized Irradiance for a non-tracking array.

Lunar surface temperature must also be considered and factored into a power system design. Figure 2 shows the inferred lunar equatorial diurnal surface temperature data from the Diviner Lunar Radiometer Experiment on the Lunar Reconnaissance Orbiter (LRO) [Ref. 1]. Peak temperatures at noon reach about 117 C (390 K) and -173 C (100 K) during night.

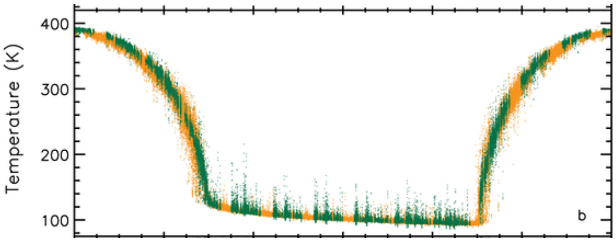

Fig. 2. Lunar equatorial surface temperatures

It is expected that the array temperature will be near the same as the surrounding surface. The high temperature will reduce array efficiency from the 28 C standard and will result in increased array area. The power output of RPS will also be effected whereby daytime power will be lower compared to that during the night. Figure 3 shows the solar array efficiency as a function of surface temperature.

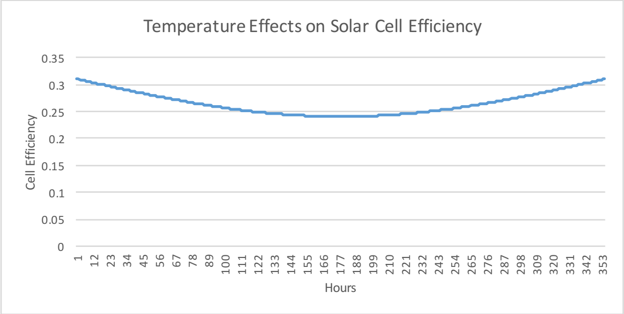

Fig. 3. Solar cell efficiency as a function of lunar surface daytime temperatures.

The data shown in Figure 3 is based on the triple junction $GaInP_2$/GaAs/Ge cell with a nominal efficiency of 29.4% at 28 C (301 K) and 1 AU. The solar cell efficiency drops to ~24% during lunar noon and increases near dawn and dusk. No decrease in array performance is accounted for ultraviolet radiation degradation nor dust on the array panel.

Both the US and USSR utilized solar based power systems on the Moon on the Surveyor and Lunokhod missions. Surveyor used an array with rechargeable AgZn batteries utilizing thermal management including; thermal paints, insulation and electric heaters for the battery and electronics. Surveyor 7 did survive one lunar night, but mission operations was terminated prior to the subsequent lunar night. The Lunokhod rover used a lid to encapsulate the entire rover including the array and utilized radioisotopes [Ref. 2] to provide heat for nighttime survival and the mission continued for about 11 months.

The first science experiment package on Apollo 11 was powered by a solar array and used two 15 Wth radioisotope heaters for night survival. Communications with the experiment station was achieved the next lunar day but signals were lost prior to lunar noon.

III. RADIOISOTOPE POWER SYSTEM CONSIDERATIONS

RPS have a distinct advantage for operating in the lunar environment and had been used successfully during the Apollo missions. Utilizing isotope fuel allows independent operation from the Sun and does not require energy storage batteries as a main nighttime power source. However, a smaller battery could provide load leveling for certain episodic operations requiring power above the baseline power output. This would allow a smaller RPS unit minimizing amount of isotope required. The Curiosity rover utilizes this approach where the MMRTG can charge the battery to support events requiring power loads above the MMRTG output.

Another advantage is the heat generated by the natural decay of an isotope. This heat can be easily channeled to components requiring specific operating temperatures such as electronic parts and batteries via heat spreaders or active cooling loops such as that on Curiosity rover. The waste heat would eliminate the need for electric heaters and the mass associated with the additional battery power. The lunar thermal environment will affect the RPS electrical output such that the higher effective radiator sink temperature will lower the power output. Figure 4 shows the estimated power output between lunar day and night for the MMRTG and enhanced-Multi-Mission Radioisotope Thermoelectric Generator (eMMRTG) [Ref. 3]. The power swing for the MMRTG is about 2-3 We and about 5-6 We for the eMMRTG.

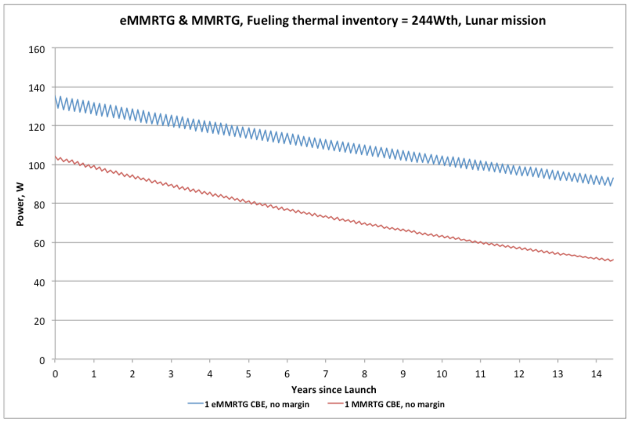

Fig. 4. Power output on the lunar surface for the MMRTG and eMMRTG

IV. SOLAR AND RPS COMPARISON

A top-level trade was performed to highlight the mass comparison of current RPS and solar power technology. A lunar equatorial mission requiring 100 We throughout the lunar day and night was used for the comparison. Using the data shown in Figures 1 to 3 and optimizing for total system mass, the solar array is 3.4 m^2 and ~10 kg. For a flight proven Li-ion battery (46.8 kWh) discharged to 90% of its capacity the battery mass is ~432 kg. The mass of the MMRTG is 45 kg as compared to 442 kg solar equivalent system.

Additionally, the Li ion battery temperature should not drop below -5 C during discharging without derating battery capacity. A first order heat loss calculation for the 100 We day/10 We night case showed about 10 Wth heat loss for a battery insulated with 25 layers of Multi-foil insulation. To maintain -5 C battery temperature and factoring the heat generated due to battery inefficiencies during discharge, requires an additional 10 We for thermal management. Therefore, the battery mass and volume would double to supply a total of 20 We during the lunar night.

Thus, a solar power system providing the same capability as an RPS is not practical. Alternatively, if the nighttime power needed was only 10% or less, the mass of solar based system would be more reasonable. Therefore, if a mission requires equal day and night power levels, RPS is truly enabling from a mass perspective. The selection of solar or radioisotope based power system will be highly dependent on the specific mission goals and associated instrumentation and mission operations plan.

For lunar missions designed to fully prospect or explore permanently shadowed regions, RPS might be the only viable option, or low power fission systems for missions with higher power requirements beyond reasonably achievable with prudent utilization of Pu-238 inventory. Solar power systems for this application would require batteries for all operations within the crater. Reasonable battery mass on a rover will limit the time, distance and quality of science the rover could accomplish before returning to the crater rim for recharging. However, a RPS powered rover could sample many more locations to determine the existence and amount of water ice for example. As an example, a proposed mission prospecting for water ice is the Planetary Volatiles Extractor. This device is mounted on a rover and cores into the lunar regolith. The coring fines are then confined and heated to liberate volatile vapors and then condensed and stored. The concept, drilling 4 operations in 24 hours, requires 5 kW-hr of electric energy and 77 kW-hr of thermal energy [Ref. 4].

V. FUTURE RPS SYSTEMS

Advanced RPS concepts utilizing dynamic power conversion can offer similar power of current RTG technology with about 25% of the isotope fuel or four times the power with the same amount of fuel. This increase in heat-to-electric efficiency becomes more significant for missions requiring higher powers in the multi-hundred-watt range, such as, rover prospecting for volatiles in lunar polar craters, propellant production, and for possible future human mission activities. Two technologies that have been widely studied over the years for advanced RPS applications are based on the Brayton and Stirling thermodynamic cycles. Typically, Brayton scales favorably to higher power levels and Stirling to lower power applications. Figure 5 shows the Brayton converter's turbine, alternator and compressor and the Stirling displacer, power piston and linear alternator.

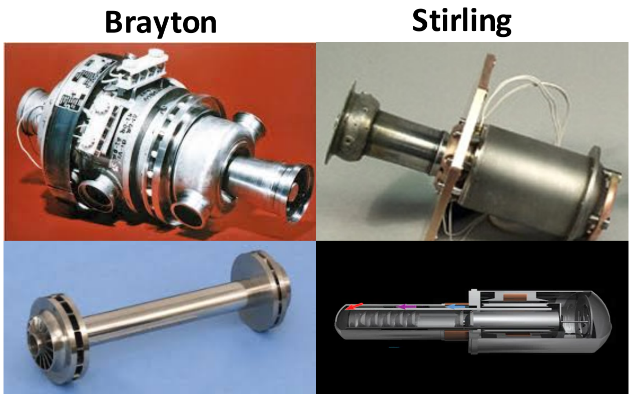

Fig. 5 Brayton and Stirling Convertors

Total system efficiency for these systems, including controller avionics, typically range between 20% to 25%. Thus, for the same amount of fuel as the MMRTG, power output would approach 400 We.

In addition to science missions, dynamic isotope systems (DIPS) were evaluated back in the early 1990's during the NASA Space Exploration Initiative (SEI) [Ref 5]. DIPS systems ranging from 500 We to 2.5 kWe were investigated to support human missions with extended science applications [Ref. 6]. Figure 6 shows a concept that would have its own mobility system to maximize its usefulness at a lunar or Mars base. The concept was that not only additional electricity but heat could be provided for habitats at night when astronauts would not be performing extravehicular activities (EVAs). The mobility feature increased the utility value of the Pu-238 fuel such that it could be used by multiple surface assets of a human outpost or base.

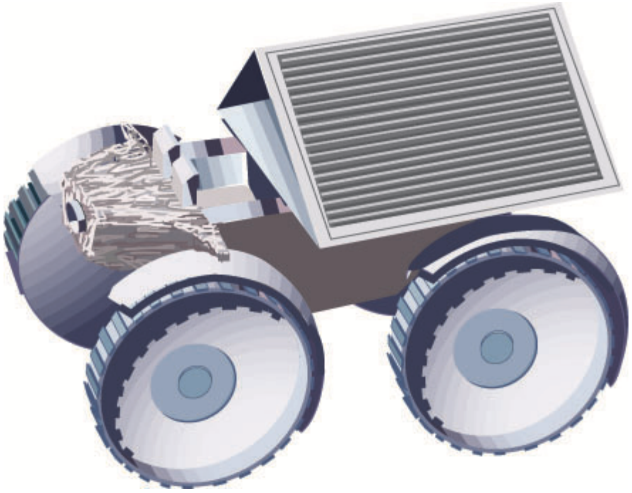

Fig. 6 Notional DIPS power system

For example, the DIPS cart could provide power for science stations remotely located from the base, robotic and crewed rover applications, drilling and ISRU processes.

VI. CONCLUSIONS

The lunar surface poses a significant challenge for a power system design. The vast temperature range and long lunar night are major hurdles to overcome. As shown with the power system comparison, energy storage has a significant mass impact for solar power based designs. RPS has a distinct advantage because its energy production is essentially limitless. Understandably, the quantity of Pu-238 available and the amount committed to any particular mission needs to be evaluated for the spectrum of future exploration destination priorities.

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