Concept for a Radioisotope Powered Dual Mode Lunar Rover

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Abstract. Over three decades ago, the Apollo missions manifestly demonstrated the value of a lunar rover to expand the exploration activities of lunar astronauts. The stated plan of the new Vision for Space Exploration to establish a permanent presence on the moon in the next decades gives new impetus to providing long range roving and exploration capability in support of the siting, construction, and maintenance of future human bases. The incorporation of radioisotope power systems and telerobotic capability in the design has the potential to significantly expand the capability of such a rover, allowing continuous operation during the full lunar day/night cycle, as well as enabling exploration in permanently shadowed regions that may be of interest to humans for the resources they may hold. This paper describes a concept that builds on earlier studies originated in the Apollo program for a Dual Mode (crewed and telerobotic) Lunar Roving Vehicle (DMLRV). The goal of this vehicle would be to provide a multipurpose infrastructure element and remote science platform for the exploration of the moon. The DMLRV would be essential for extending the productivity of human exploration crews, and would provide a unique capability for diverse long-range, long-duration science exploration between human visits. With minimal reconfiguration this vehicle could also provide the basic platform to support a range of site survey and preparation activities in anticipation of the establishment of a permanent human presence on the moon. A conceptual design is presented for the DMLRV, including discussion of mission architecture, vehicle performance, representative science payload accommodation, and equipment and crew radiation considerations.

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INTRODUCTION

The Dual Mode Lunar Roving Vehicle developed in this study extends a concept originally investigated during the Apollo program (Slaybaugh, 1969, Grumman, 1970). For extended lunar exploration it was recognized that the crewed transportation rovers that had been used to such good effect on the later Apollo missions could, with modification, provide a telerobotic exploration platform allowing long-range surveys of the lunar terrain between crewed landings. These early studies (Fig. 1) indicated the feasibility of such a vehicle, but the demise of the Apollo program meant that these studies were never given the opportunity to proceed to flight units.

Three decades later the utility of this original concept appears especially timely. The Apollo missions manifestly demonstrated the value of the crewed lunar rover to the astronaut's exploration activities. The stated plan of the Vision for Space Exploration (Bush, 2004) to establish a permanent presence on the moon in the next decades gives new impetus to providing long range roving and exploration capability in support of the siting, construction, and maintenance of future human bases. The addition of radioisotope power systems to the design further extends the capability of such a rover, allowing operation during the full lunar day/night cycle, as well as enabling exploration in permanently shadowed regions that may be of interest to humans for the resources they may hold.

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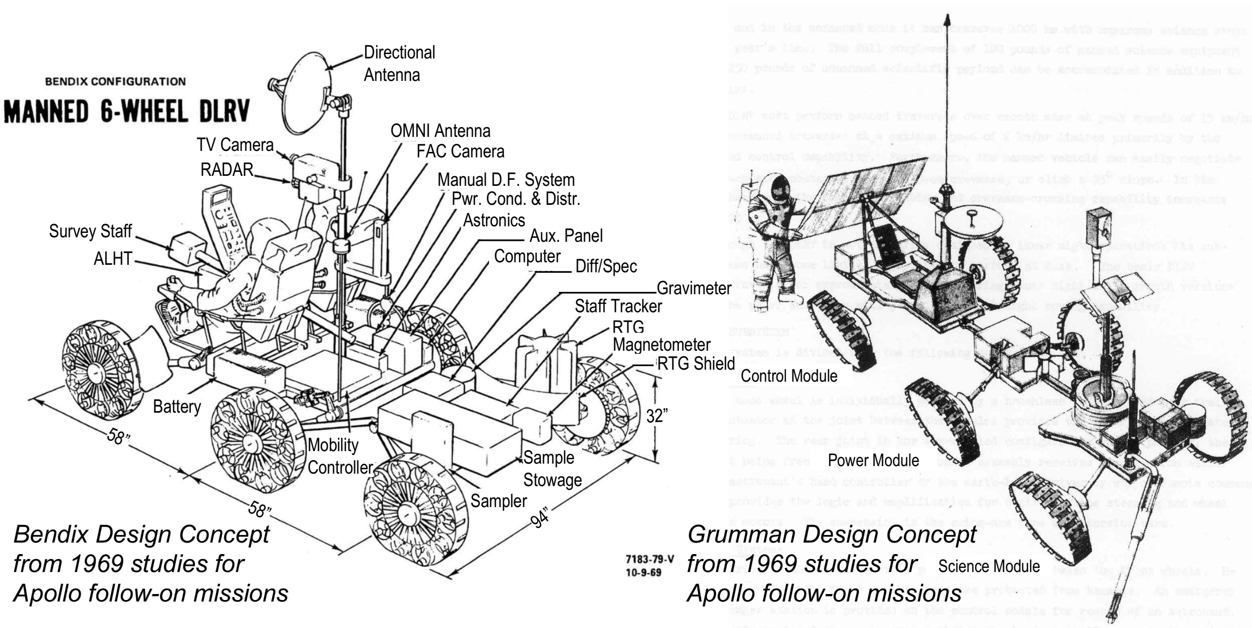

FIGURE 1. 1969 DLRV Design Studies.

CONCEPT DEFINITION

The goal of the Dual Mode Lunar Roving Vehicle (DMLRV) would be to provide a multipurpose infrastructure element and remote science platform for exploration of the moon. The DMLRV would be essential for extending the productivity of human exploration crews, and would provide a unique capability for diverse long-range, long-duration science exploration between human visits. An additional goal of the DMLRV would be to provide a reconfigurable vehicle system capable of conducting surveying and a range of site preparation activities in support of the establishment of a permanent human presence on the moon.

The DMLRV's systems would be designed to operate over a nominal lifetime of 5 years. In telerobotic operation, the rover would be capable of traversing over 1000 km of the lunar surface. Operating in conjunction with astronauts would enable the DMLRV to be serviced in the event of component failure, and would also allow for simplified deployment and instrument/payload flexibility throughout its life. These features would provide the potential for extended operational life well beyond the nominal 5-year mission duration.

Mission Architecture Overview

The mission begins with delivery of the rover on a crewed lunar lander. An assumption has been made that the DMLRV, as was the case with the Apollo Lunar Roving Vehicle, would be carried as an auxiliary payload on the descent stage of a lander. In the case of the DMLRV, the full vehicle (Fig. 2) would be carried as two separate components. The 4-wheel rover section would be self-contained and deployable by the astronauts as a fully functional single unit. The design of the 4-wheel portion of the rover is such that it could be used in the astronaut mobility application independent of the two-wheel trailer portion of the vehicle. Astronaut sorties would be limited by the duration of EVA suit life support systems, as well as the probable requirement for a "walk-back" capability. Given this limitation in the duration of astronaut sorties (predicted to be no greater than ~8 hr), the 4-wheel rover would operate in the mode on battery power, as was the case with the Apollo lunar rovers.

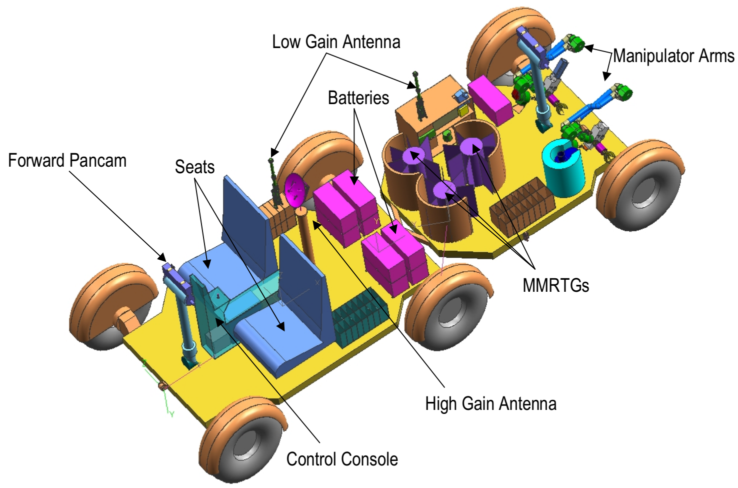

FIGURE 2. DMLRV Conceptual Design.

In order to support the teleoperation mode, a 2-wheeled trailer extension would be carried as a separate, second package on the lunar lander. Upon completion of the crewed rover operations, this two-wheel module would be attached to the 4-wheel rover by the astronauts, resulting in a configuration optimized for teleoperated long-range exploration. The trailer design provides maximum flexibility for science experiments by standardizing payload interfaces. This allows for modular "plug-in" instrumentation that could be easily removed and replaced by astronauts during subsequent missions. Similarly, the trailer itself is a modular component to the overall rover and could be completely replaced with a new unit incorporating different science capabilities, or with a unit dedicated to infrastructure tasks (e.g. excavation and grading in support of site preparation activities). The RPSs located on the trailer enable long-range teleoperated exploration by providing day/night continuous operation with minimal "down" time required for battery charging. The continuous power supply from the RPSs provides a unique capability for operating science payloads in shadowed crater regions and during the extended period of lunar night. The modular trailer design and RPS power supply are key to the versatility of the DMLRV concept, allowing a variety of potential tasks to be performed by a single infrastructure element.

The long range of the rover is intended to allow it to traverse to a subsequent landing site where it could be serviced, if necessary, and used by the next crew for human transportation. This subsequent expedition may bring additional experiment packages for incorporation into the DMLRV instrument suite for the next teleoperated exploration traverse.

Alternatively, once a promising site has been chosen for the location of a human base, a new two-wheeled module specifically designed for site preparation activities may be delivered by an astronaut crew. It is expected that preparation for a permanent human presence would require extensive regolith moving activities including grading, rock moving, and excavation to prepare for emplacement of a variety of base elements. The basic roving vehicle would provide the platform for a multipurpose site preparation infrastructure element, allowing for slow, but long-term regolith moving activities guided telerobotically from the Earth.

SCIENCE ACCOMMODATION

The DMLRV is capable of supporting a wide assortment of scientific instruments depending on mission objectives. The continuous power available from the RPS widens the range of tools that could be accommodated in the rover's instrument suite. An array of potential instruments was studied to demonstrate the versatility of the rover and its science platform in assisting astronaut explorers and performing extensive telerobotic science gathering of its own in a geological survey mission.

Instruments on the rover could be located in a variety of areas (Fig. 3). The twin Pancam masts on the rover and trailer are mounting points for lights and imagers, providing a high-resolution 360° view of the surrounding terrain.

An interchangeable science rack on the trailer would provide standardized power and data interfaces, allowing astronauts to plug in and remove modular scientific instruments as needed, enabling the rover's instrument suite to be optimized for a particular sortie including the tools best suited for the task on hand. This also expands the rover's capabilities while operating tele-robotically as the instrument inventory could be reconfigured or augmented prior to the human crew's departure.

The twin robotic arms provide mounting points for tools and imagers that are best used close-up against the surface of the samples being analyzed. The robotic arms would also be equipped with end effectors capable of grasping rock and soil samples for delivery to deck-mounted science instruments or sample storage containers. The two arms could be used in conjunction with one another for holding samples with one manipulator and analyzing the sample with the other arm's instruments. Larger tools could be mounted directly to the rover's deck as proposed with the 2.5-m drill which was included in the strawman instrument suite.

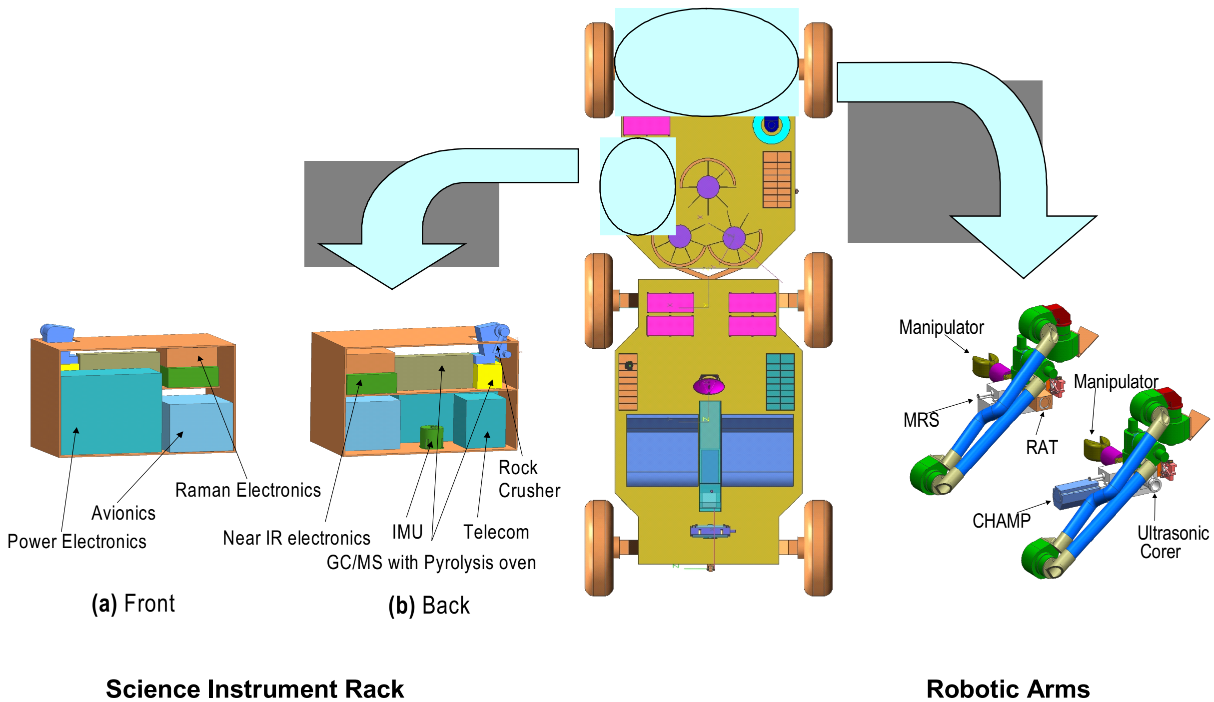

FIGURE 3. Instrument Accommodation.

POWER AND MOBILITY

The DMLRV would require three standard 110 We (BOM) Radioisotope Power Systems (RPSs) to provide for its energy requirements. This study considered the use of the Multimission Radioisotope Thermoelectric Generator (MMRTG) and Stirling Radioisotope Generator (SRG) as the power system baseline, with the former detailed here, and the latter investigated as an alternative power source. The MMRTG represents the most stressing scenario from a heat and radiation standpoint. In this concept the MMRTGs are mounted vertically on the DMLRV science trailer's deck as shown in Figure 2. Heat exchangers would be placed radially around the RPSs to limit the effects of the radiated heat on the crew and rover systems while collecting the excess heat emitted by the RPS radiator fins for use in thermal control of rover systems.

The three MMRTGs provide 330 We at BOM, falling to ~304 We at the end of the 5 year nominal mission, and down to ~279 We after an additional 5 year extended mission. The DMLRV study assumed the standard MMRTG configuration; a more compact arrangement could be provided by removing the individual RPS fins and grouping the RPS units together in a single enclosure provided with a cooling loop that could transport waste heat to a remote radiator. For power dense missions such as regolith-moving applications, such an arrangement might be pursued to accommodate an increased electrical generation capacity on the compact trailer unit. The enclosure may also provide advantages in dust protection over the finned configuration.

Rechargeable Li-Ion batteries would be used in conjunction with the MMRTGs to provide power to the rover's systems. The baseline design calls for the DMLRV to carry ten 25 A-hr Li-Ion batteries, with nine located on the rover and one on the science trailer. For crewed operation the batteries alone would provide the power to run the rover's systems, allowing the rover portion of the vehicle to operate independently of the science trailer for astronaut sorties. If needed, the rover batteries could be recharged by the RPSs on the science trailer between sorties.

When operated in the crewed mode, the rover would have access to nine 25 A-hr batteries in the baseline design. The rover's range in this mode is largely limited by the power draw of the wheel actuators, which is impacted by the rover's mass and the velocity traveled. Table 1 shows the maximum range of the rover while traveling at 8 km/hr (average speed of Apollo LRV) with various payload masses. For reference, it is estimated that the payload mass of two astronauts in EVA suits would be about 400 kg.

TABLE 1. Rover Operating Duration and Range as Function of Payload Mass, Driving at 8 km/hr.

Payload Mass (kg)	***Driving Duration (hr)***	***Total Driving Range (km)***
800	5.1	40.8
750	5.3	42.6
700	5.6	44.6
650	5.9	46.8
600	6.2	49.2
550	6.5	51.8
500	6.8	54.6
450	7.2	57.8
400	7.7	61.2

In teleoperated mode, the baselined DMLRV would operate as a complete unit with Li-Ion batteries along with its full RPS compliment. The baseline design with 303.6 We (EOM) from three MMRTGs would be capable of over 30 hrs of continuous driving at 2 km/hr before needing to stop for an equivalent period to recharge its batteries. In an operational scenario, the rover would likely make frequent stops to perform science and data transmission operations and so would be unlikely to need to drive for such an extended period of time. During the stationary periods, power draw would be greatly reduced and the batteries would recharge, allowing the rover to operate essentially without interruption. The ability of the rover's wheel contact sensors and imagers to conduct science while the rover is traversing greatly increases the amount of ground the DMLRV could survey while traversing and improves the rover's ability to spot signs of local water and other promising targets. The contact sensors do require the rover to travel at $\leq$0.36 km/hr, so the rover would have to slow down from its nominal 2 km/hr cruising speed to utilize them to best effect. At these reduced velocities, the DMLRV's batteries would be in a continuous charging state, extending its driving duration indefinitely.

The DMLRV's RPSs alone provide ample electrical power to accommodate the ~280 We the entire strawman instrument suite would draw if operated simultaneously, meaning that power generation would not constrain the science instruments in normal operations. This available power leaves open for consideration the option of much more power intensive instruments in the science package.

MASS

The baseline DMLRV system design has an estimated total mass of ~930 kg (CBE + 30% margin) including a strawman instrument suite. The individual rover and trailer sections have masses of 445 kg and 485 kg, respectively. The mass breakdown by subsystem is shown in Table 2. The majority of the total mass is made up by the structure and power system. The DMLRV's versatile battery/MMRTG power system and sturdy frame for handling heavy loads make the system heavier than the Apollo LRV, but this new design offers significantly enhanced capabilities relative to the earlier rover.

To support lunar infrastructure development, a large payload capacity would be required to allow for hauling regolith or towing equipment into place. When operating in a science and exploration role, this capacity could translate into large science or supply loads. The DMLRV concept was designed to accommodate a maximum payload of 800 kg, of which 400 kg would be allotted to the two suited astronauts with the remainder being open for samples and equipment. In the teleoperated mode, the total science and sample mass could be increased to the entire 800 kg payload capacity. This would allow for considerable sample storage capability for the DMLRV's long teleoperated missions.

TABLE 2. DMLRV Mass Summary.

Subsystem	*Mass (kg)*	*Margin (%)*	*Mass with Margin (kg)*	*Notes*
Rover Section	**342**	**30%**	**444.7**	
Structures/Mechanisms	125.8	30%	163.5	Projected from tubular frame concept
Human Operations	8	30%	10.4	Includes seats and instrument console
Mobility and Drive	43.2	30%	56.2	Wheels and Fenders
Thermal	16	30%	20.8	Heat pipes and radiators
Guidance and Navigation	2.5	30%	3.3	IMU, cameras
Avionics	16.8	30%	21.9	Two identical single string systems
Power	100.8	30%	131	Batteries and control electronics
Telecom	17.6	30%	22.9	Transmitters, 20 W TWTAs, antennas
Cables	7.5	30%	9.8	
Instruments	3.8	30%	4.9	Pancam, wheel contact sensors
Trailer Section	**373.3**	**30%**	**485.3**	
Structures/Mechanisms	87.6	30%	113.88	Estimated from rover mass
Mobility and Drive	21.6	30%	28.08	Wheels and fenders
Thermal	15	30%	19.5	Heat pipes, HXGRs, and radiators
Avionics	18.3	30%	23.8	Two identical single string systems
Power	155.7	30%	202.4	3 MMRTGs, battery, control electronics
Telecom	8.7	30%	11.3	Transmitters, 20 W TWTAs, antennas
Cables	7.5	30%	9.8	
Instruments	59	30%	76.6	Strawman instrument suite

RADIATION CONSIDERATIONS

The rover and its crew would be exposed to two different radiation environments during their stay on the moon: the radiation field of the RPS, and the background radiation on the lunar surface. The lunar environment exposes the rover and crew to both galactic cosmic radiation (GCR) and the solar particle flux from the Sun. Interactions of GCR with the lunar regolith also generate neutrons, which would scatter back up to impact the systems. The long duration of the mission would expose the electronic systems of the rover to powerful Solar Particle Events (SPE). It is assumed that the astronauts would take cover in such an event; thus, the dose from SPEs is not taken into account for the astronaut dose rate while on the rover.

Dose to Rover Equipment

The three MMRTGs on the rover would represent a source of neutron and gamma radiation to the instruments and electronic components. The higher radiation field of the MMRTG (compared with the SRG) was used to represent the most stressing case for the doses to the crew and equipment. Table 3 shows the total 5-year mission dose received by the two electronics chassis and the Pancam units. These doses were based on rates calculated from analyses performed by JPL on the radiation field produced by MMRTGs. Rates for SPEs were calculated for an average year.

The results indicate that the maximum total dose to the rover electronics would be ~ 33 krads for the 5-year nominal mission duration, the majority resulting from SPEs, requiring a minimum of 66 krads hard parts or additional shielding to ensure safe operation. This level is easy to accommodate with existing hardened electronics and is not expected to pose a challenge to the mission.

TABLE 3. DMLRV Radiation Dose Estimates for Selected Subsystems.

Source	*Avionics Rack Front*	*Avionics Rack Rear*	*Pancam Head Front*	*Pancam HeadRear*
Total Ionizing Dose over 5 yrs (rads(Si) behind 100 mils Al)				
MMRTG Total	**429.5**	**27971**	**191.4**	**666.6**
Environment Total	**7530**	**7530**	**7530**	**7530**
GCR	36.5	36.5	36.5	36.5
SPE	7490	7490	7490	7490
Total Mission	**8121.2**	**23622.4**	**8728. 9**	**9929. 8**
Displacement Dose from Neutrons over 5 yrs (# 1MeV n/cm^2)				
MMRTG Total	**1.91E+10**	**1.36E+12**	**8.39E+09**	**2.99E+10**

Dose to Crew

Preliminary analysis of the radiation fields produced by the MMRTGs suggests that the dose levels would be low enough to allow safe operation of the rover with the science trailer attached for crewed operation. Results of this analysis are shown in Table 4. This table also presents results from an assessment of the same design using four SRGs in place of the three MMRTGs. The hourly weighted dose rate to an unprotected human from the Stirling powered trailer would be approximately 7.8 mrem/hr. This is only 23% of the background dose the astronauts would accrue from GCR while operating the rover. The gamma ray contribution to the dose could be further reduced by the addition of shielding at the cost of added mass. These calculations do not take into account any shielding due to the astronaut's suits or scattering from the lunar regolith, both of which would affect the results.

TABLE 4. Estimated Radiation Dose to Crew While Using DMLRV Trailer.

Crew Dose Rate in Right or Left Seat	*RPS Gamma Dose Rate (mrem/hr)*	*RPS Neutron Dose Rate (mrem/hr)*	*Background GCR Dose Rate (mrem/hr)*	*Total Weighted Dose Rate (mrem/hr)*
MMRTGs	16.2	31.7	33.4	81.3
SRGs	3.3	4.5	33.4	41.2

ALTERNATE POWER SYSTEM DESIGN

While the preceding mission analysis assumed an MMRTG-based power system, the MMRTG actually represents the more stressing example from a thermal and radiation perspective. In fact, the nature of the DMLRV's proposed mission and its operation may favor the SRG for this application. As the rover would be intended for crewed operation, the lower dose accrued from the SRGs implies that they would be the preferred choice from a radiological point of view. The four SRGs (three primary and one spare) would incorporate a total of eight GPHS modules compared to the 24 modules carried on the three MMRTGs, resulting in a considerable reduction in the dose to the electronics and crew. In addition, their lower heat output makes radiated thermal energy less of a concern. The lower mass of the SRGs allows for the addition of the fourth (spare) unit with nearly the same total mass as three 3 MMRTGs while yielding an additional 110 We generating capacity to the 330 We baseline at BOM. This extra unit would enhance power system reliability and allow continuous operation while driving in telerobotic mode, potentially increasing the distance that could be covered during a teleoperated mission.

Should the SRGs be used, they could be placed crosswise on the bed of the science trailer, as shown in Figure 4. This arrangement reduces open deck space on the science trailer but still provides ample room for science instruments on the outer portions of the trailer platform. Other potential arrangements of the SRGs could be accommodated, with configuration being made more flexible as a result of their lower thermal and radiation emissions. As mentioned, the DMLRV would carry a redundant fourth SRG per current NASA and DOE guidelines (Casani, 2001) increasing the electrical power available to the rover. The four SRGs together would produce ~440 We at BOM, and would drop to ~419 We after 5 yrs at EOM, and down to ~398 We after 10 years of operation. While the possibility of a unit failure may be higher with the SRGs, a single failure would result in a drop in electrical power down to the level of the baseline MMRTG mission, leaving the DMLRV still fully capable of completing its mission.

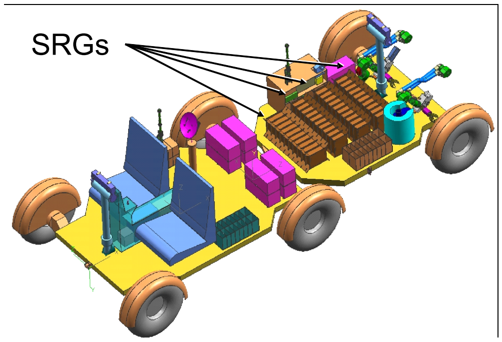

FIGURE 4. DMLRV SRG-Powered Concept Power System Layout.

CONCLUSION

The concept developed in this report is a new look at an old idea. The utility of an unpressurized roving vehicle for astronaut exploration was demonstrated in the Apollo program. The expansion of roving capabilities through the incorporation of a long-lived radioisotope power source enables a significant extension of the rover's capabilities when used in an unmanned, teleoperated mode. The ability to perform long range, long duration science and exploration, independent of solar illumination, has the potential to add a great deal to our understanding of the lunar geology over large areas. In further support of the Vision for Space Exploration, this concept can directly support the establishment of a lunar base through site exploration and characterization using a focused science instrument payload. Once the site is selected, the addition of regolith-moving equipment to the basic vehicle can provide the tools needed to prepare the site for human occupation.

This study has only begun the process of design and study of the applications in which such a vehicle could be used. Further work remains to delve deeper into areas such as long-range mobility and suspension components, telerobotic operations, thermal control, and dust mitigation and control. It should be noted however that none of these areas represent new technologies; all have been addressed by past design teams, including both the US Apollo missions and the Soviet Lunakhod rovers. A particular new application that warrants a more detailed investigation is the adaptation of the DMLRV to the site preparation role. One major driver for the development of such a vehicle may be the potential it holds for allowing long term regolith moving and excavation activities in support of the establishment of a permanent human presence on the lunar surface. The limits of this study allowed only a very cursory evaluation of the potential of the rover for such an application, but the design has been made as flexible as possible in expectation of a desire to more fully investigate this increasingly valuable option.

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