Comparison of Radioisotope Power Systems to Enable the Endurance Mission Concept

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***Abstract*—NASA has a long history of using Radioisotope Power System (RPS) technologies to enable space missions. Today, NASA's RPS Program, working with the Department of Energy, deliver RPS to NASA missions to enable the exploration of cold, dark, dusty, and harsh environments. The RPS Program manages the investments made to develop RPS products to enable future missions. To better understand what technologies could most benefit current and future missions, the RPS Program conducts mission and systems studies. This study was undertaken to understand the impact of different RPS technologies on a lunar surface rover mission concept.**

The Endurance mission concept is one of the mission concept studies for the 2023-2032 Planetary Science and Astrobiology Decadal Survey. It would be an autonomous, rover mission enabled by the RPS to traverse 2,000 km on the lunar surface collecting and delivering samples to the Artemis basecamp near the south pole. The baseline RPS used in the design concept for the four-year mission is the Next Gen RTG (NGRTG).

To gain insight into the power requirements of a lunar rover mission concept, the RPS Program Office and the Jet Propulsion Laboratory's (JPL's) Team-X conducted a study comparing the impact of various RPS technology options using the Endurance rover concept as a baseline. The study generated parametric point-designs that analyzed one of two different thermal subsystem designs and, notably for the power system, one of four RPS products: MMRTG, NGRTG, Plutonium Oxide-based Stirling RPS, and an Americium-based variant of Stirling RPS. From the RPS Program's perspective, the MMRTG is the current state-of-the-art, the NGRTG is a planned next generation product, and both Stirling RPS variants are potential future product offerings. The thermal and mechanical design and configuration were altered to accommodate the RPS; other variables were kept constant throughout the study, facilitating the comparison of different point-designs.

This paper provides a summary of the results of the Team-X study for the seven point-design that were evaluated. The metrics for evaluation were the estimated mass of the rover and the estimated mission duration; these metrics were selected to track the viability of rover delivery via a Commercial Lunar Payload Service (CLPS) lander, and in meeting the four-year mission duration requirement. Overall, the results showed that achieving mission closure for the Endurance rover mission is possible with any of the specified power systems and either of the heater architectures (depending on the power system implemented).

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1. INTRODUCTION

To help advance our understanding of the universe, NASA has relied on Radioisotope Power Systems (RPS) for over 60 years. From RPS-enabled payloads on the lunar surface throughout the Apollo missions to Voyager 1 & 2 at the outer reaches of the solar system, RPS have been enabling missions since the late 1960s and will continue to do so in the future. Given their key features of providing continuous electrical and thermal power over long mission durations, RPS enable the pursuit of uninterrupted science in the darkest, coldest, most inaccessible and extreme environments of the solar system.

To maintain and build on this storied legacy, the RPS Program manages NASA's investments in RPS to meet the needs of future space exploration missions. The RPS Program is a collaborative effort involving multiple NASA centers: NASA JPL, the Johns Hopkins University Applied Physics Laboratory (JHUAPL) and the U.S. Department of Energy. Within NASA, the RPS Program reports to the Planetary Science Division (PSD) of NASA's Science Mission Directorate (SMD); the PSD is typically the organization that formulates and implements the majority of RPS missions. Primary management of the RPS Program is conducted out of NASA's Glenn Research Center (GRC).

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Recently, NASA has received the Planetary Science and Astrobiology Decadal Survey (PSADS) 2023-2032 report (Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032) that details science objectives and mission concept recommendation for the next decade. Several studies were assigned to support the PSADS efforts, including several mission concepts using RPS. To gain better insight into the power requirements of a lunar rover mission, the RPS Program Office conducted a study comparing various RPS technology options for the Endurance mission concept (the lunar surface rover mission recommended by the PSADS).

Part of the RPS Program's role is to conduct mission analysis to get a baseline understanding of the RPS "mission pull" (i.e., developing technologies to meet the performance needs of mission concepts) and RPS "technology push" (i.e., mission concepts making use of advances in the performance of key technologies). This paper represents the outcome of a study to better understand what the impact of these different RPS products could be on the performance and feasibility of a lunar surface rover mission.

Section 2 of this paper provides context on what the Endurance mission concept is and why it matters. Section 3 provides background on JPL's Team-X and the study that was conducted, including descriptions of the key inputs to the study. Section 4 reviews the results of the Team-X study and Section 5 provides a summary.

2. THE ENDURANCE MISSION CONCEPT

The Endurance mission concept study was requested by the panel on Mercury and the Moon as part of the 2023–2032 Planetary Science and Astrobiology Decadal Survey. Endurance is an evolution of the Intrepid planetary mission concept study (PMCS) [1], which was designed to traverse >1,800 km on the lunar nearside to address priority science questions focused on lunar magmatism. Intrepid used solely remote sensing and non-contact instruments, and did not have the capability to collect, cache, or return samples. The Mercury and Moon panel was impressed by the Intrepid concept and sought to understand if an Intrepid-like architecture could be applied to addressing the longstanding goal of South Pole Aitken basin (SPA) sample return. A further request of the study was to compare architectures using robotic sample return (Endurance-R) with sample return via transfer to Artemis astronauts (Endurance-A).

SPA's importance has been long recognized, and SPA Sample Return (SPA-SR) has consistently ranked as one of the top priorities for planetary exploration in the past two Decadal Surveys [2, 3], and the top priority for lunar exploration [4, 5]. While motivated by many of the same science questions, Endurance is very different from previous SPA-SR concepts. The ability to essentially combine twelve SPA-SR missions into one and the enhanced ability to choose samples through mobility (as opposed to sampling from a stationary lander), mark Endurance as a radical departure from previous approaches. In addition, the nearly order-of-magnitude increase in potential sample mass enabled by the presence of Artemis astronauts further enhances the value of this mission. All of this led the Committee on the Planetary Science and Astrobiology Decadal Survey (PSADS) to recommend Endurance-A be implemented as the "highest priority of the Lunar Discovery and Exploration Program" [6]. As further noted in the PSADS report, "Return of Endurance-A samples by Artemis astronauts is the ideal synergy between NASA's human and scientific exploration of the Moon, producing flagship-level science at a fraction of the cost to PSD through coordination with Artemis."

The baseline traverse for Endurance is shown in Figure 1. Endurance would land in the center of SPA and traverse out of the basin via two other large, ancient basins—Poincaré and Schrödinger—before rendezvousing with Artemis astronauts near the lunar south pole. Endurance's science objectives require exploring these diverse, distinct regions, which are often separated by 100s of kilometers. Each large basin contributes to a different part of the Moon's impact chronology, and volcanic deposits and other unique terrains along the traverse (e.g., high-thorium areas) provide insight to the Moon's thermochemical evolution.

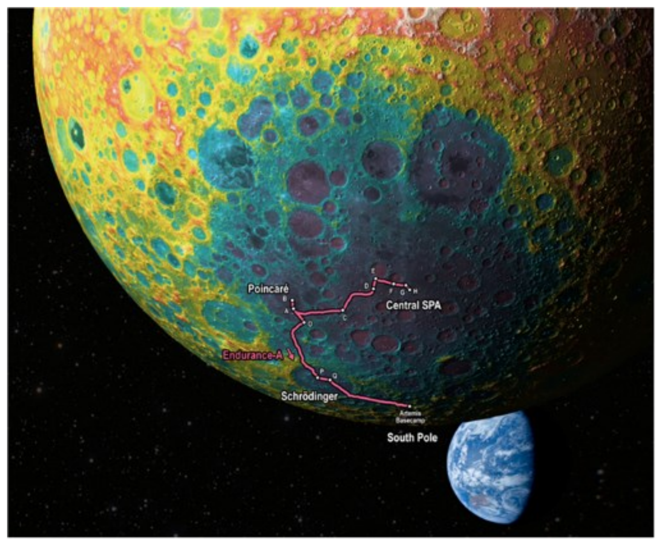


Figure 1. A notional Endurance traverse (pink) draped on a topography map of the lunar farside (blue is low, red is high). SPA is the prominent, large, basin dominating the southern lunar farside.

The Endurance mission architecture is, consisting of a single rover element delivered to a landing site in the central SPA by a dedicated lander. The current baseline configuration for the Endurance rover concept is shown in Figure 2. The rover concept is a 4-wheel design, with all four wheels powered and steerable. Suspension would be a passive design comprising a single rocker mounted on the front of the rover with a 4-bar mechanism to allow the front wheels to maintain a vertical orientation when traversing obstacles. A mast with a pan/tilt head is mounted to the front of the rover, providing an elevated platform for navigation cameras (redundant stereo pairs), science cameras, and a LIDAR. A similar redundant pair of navigation cameras is also provided on a fixed mount at the rear of the vehicle, allowing for driving in either direction. Telecommunications is currently baselined as S-band, using a UST-Lite transponder coupled with a 5 W power amplifier to communicate with an orbital relay through a steerable 0.75 m high gain antenna. An omnidirectional low gain antenna is also provided for lower rate communications.

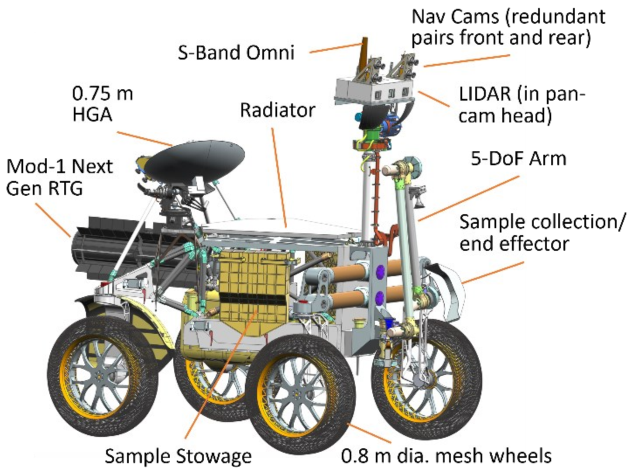


Figure 2. Endurance Rover Concept.

Rover avionics including redundant flight computers, motor controllers, and vision processing, as well as electronics for the rover instrument suite, are contained in a thermally controlled warm electronics box (WEB) located on the bottom of the main rover body. Waste heat from the WEB is rejected to space through a top-mounted radiator. Heat is transferred from the WEB to the radiator through a loop heat pipe that passively decouples the radiator when temperature drops at night.

Communications during its mission on the far side of the moon would be relayed through one or more telecom orbiters, assumed to be available in the time frame of the mission. Driving requirements for this mission derive from the need to traverse an unprecedented distance (>2,000 km) across an unexplored region of the lunar surface in a relatively short period of time (<four years). The rover concept resulting from this set of requirements emerged from a number of trades that evaluated prior and current experience with Mars rovers, as well as taking advantage of the large amount of work performed during the Apollo program to characterize and assess mobility in the lunar environment. This led to a concept that places an emphasis on maintaining design simplicity (e.g., passive suspension) while providing robust functional redundancy (e.g., four driven wheels, all steerable) to maximize the likelihood of mission success.

The need for high sustained traverse speeds drove two key design choices: onboard autonomy, and RPS as a power source. A trade study was performed to assess the viability of using a solar powered rover, based on a concept originally developed for the Intrepid PMCS. Endurance's need for long-distance night driving (not possible with the solar concept) strongly favored an RPS option to enable a shorter mission duration. Further, given that Endurance traverses all the way to the south pole, the solar concept's traverse planning was found to be severely complicated by the low solar elevation and prevalence of long and persistent shadows that would have to be negotiated as the rover approached the Artemis rendezvous. In addition, the large mass of batteries required to provide overnight survival heating would impact rover power requirements and required lander capability. While it cannot be shown that the solar rover is infeasible for the Endurance mission, the additional mass, mission duration, traverse distance and significant risk involved led to the choice that the mission be RPS-powered.

The NGRTG (Mod-1) was chosen as the baseline power system for the mission concept. The planned NGRTG would produce more than twice the power of the MMRTGs used on the current Mars rovers, providing sufficient energy to support driving at the 1 km/hour nominal speed and complete the mission well within the targeted 4-year duration.

Notional Concept of Operations

The mission requirement of driving 2,000 km within a four-year period is accomplished through the careful design of the Concept of Operations (ConOps), which in this case is based on the decadal survey ConOps . The overall mission operations are divided into six components: commissioning and rendezvous, sampling, day-drive scenario, night-drive scenario, fault margin, systems margin. A high-level overview of all six components of the ConOps are below:

Commissioning & Rendezvous—This component represents a fixed time at the beginning and end of the mission for initial checkout and handoff of the samples to astronauts.

Sampling—This component accounts for 14-days of sampling operations at each of the twelve sampling sites.

Day-Drive Scenario—The day-drive scenario accounts for all operations throughout the Lunar day. It is broken up into three high-level sequential activities: drive (for 2 km in 3.2 hours), stop for telecom (1 hour), and stop for charging (variable duration). The drive activity is further broken down into loops of 300 m traverses (20 minutes) followed by localization stop (10 minutes). A depiction of the day-drive scenario is shown in Table 1.

Table 1. Sequential activity blocks for the Day-Drive Scenario.

Drive 2,000 m in 3.2 hours	
	Day Traverse Mode 300 m in 20 min
	Localization Stop Mode 10 min
Telecom Stop Mode 1 hour	
Charge Stop Mode Duration varies between BOM & EOM	

Night-Drive Scenario—The night-drive scenario is more complex than the day-drive scenario; the night-drive scenario activity sequence starts with warming up the rover, followed by a drive (for 2 km in 6.4 hours), followed by a 1-hour telecom stop and a variable duration charging stop. The 2 km drive is broken into 300 m segments and 10 minutes localization stops; the 300 m segments are further broken into 10 m drive segments followed by localization stops. A depiction of the night-drive scenario is shown in Table 2.

Table 2. Sequential activity blocks for the Night-Drive Scenario.

Mode	Duration
Warm-Up Mode	Varies based on the charge stop duration
Drive	2,000 m in 6.4 hours
— **Drive**	300 m in ~50 min
—— **Night Traverse Mode**	10 m in <1 min
—— **Localization Stop Mode**	1 min
— **Localization Stop Mode**	10 min
Telecom Stop Mode	1 hour
Charge Stop Mode	Duration varies between BOM & EOM

Note that the warm-up mode in the night-drive scenario is only applicable to the electrical heater architecture; the waste-heat capture fluid loop does not need the warm-up mode stop. More detail on the electrical heater architectures is provided in the following section.

Fault Margin—A fixed time accounting for the response to and the recovery from major and minor faults throughout the drive. The fault margin is calculated as a function of the total traverse distance of 2,000 km. The fault margin policy is informed by the operations history of the Mars Science Laboratory and Perseverance rovers.

Systems Margin—This is a variable duration to account for unexpected slowdowns throughout the mission duration. The systems margin is calculated as 33% of the previous five components.

3. The Team-X Study

Team-X, part of the JPL Innovation Foundry, is NASA's mission design center at JPL. Established in 1995, Team-X is the longest-standing concurrent engineering design team for space mission concept development. Subject matter experts in spacecraft subsystems, systems engineering, instruments, science, cost and programmatics work collaboratively through a finely honed process informed by over 1,700 completed studies.

Team-X positions, staffed by trained members of the 'doing organizations' at JPL, ingest customer teams' concept requirements and constraints, develop subsystem-specific design solutions, and combine these through JPL's Institutional Modeling Environment to produce system-level solutions that meet technical constraints with formulation-appropriate margins (e.g., launch vehicle capacity, power and link budgets). Should cost estimation be a customer-requested output, JPL's Institutional Cost Models, also maintained by the doing organizations, are integrated into the process, providing real-time estimates of total mission cost down to a Work Breakdown Structure-3 (WBS-3) level of detail.

The Team-X business model [7] and co-located activity have enabled rapid development of technical and financial 'Point-Design' existence proofs for numerous competed mission concepts that have gone on to be selected for implementation by NASA, including Psyche [8], VERITAS, and InSight. Team-X has conducted studies for the Planetary Science Decadal Survey, and recently has been tapped by NASA to investigate design trades for the Artemis Human Landing System and the Mars Sample Return mission.

For this specific study, the initial customer contact was followed by a planning meeting in which the included and excluded scope of the study was agreed upon, meshing broad-ranging customer desires with the capabilities of Team-X. During this negotiation it was decided to use the Endurance rover's latest iteration as the design reference mission to facilitate clean comparisons amongst the RPS and thermal control options investigated (more in following subsections).

Between the planning meeting and the study itself, two pre-sessions were conducted to 'prepare the field'. During these sessions (3 hours + 1 hour), the baseline endurance rover architecture (using the NGRTG and electrical heaters) was ingested into the Team-X modeling environment, subsystem-by-subsystem, at the lowest level of component detail currently available. This baseline MEL and the power mode drive scenario ConOps were integrated into a full point-design to be cross-checked with the mass, power, and drive-time requirements and margins that had been independently determined by the Endurance team prior to this study's initiation. This served as a validation of the Team-X models and ConOps setup as appropriate for this study, with the MEL, PEL, and mission duration matching the Endurance project values to within 5%.

The full study (investigating the remaining 6 viable options) was conducted in four 3-hour sessions over the course of a single week in the JPL Foundry's Project Design Center facility. The viable options for the study were differentiated along two figurative axes: the type of RPS product to be used and the thermal subsystem architecture.

The RPS Product Axis

The four different RPS that were used throughout the Team-X study were: 1) Next Generation Radioisotope Thermal Generator (NGRTG), 2) Multi-Mission RTG (MMRTG), 3) Plutonium Oxide-based Stirling RPS, and 4) Americium-based Stirling RPS.

The NGRTG is a near-term RPS that builds on the General-Purpose Heat Source – RTG (GPHS-RTG) [9], which has been used for many missions including Cassini and Pluto New Horizons [10]. The GPHS-RTG (like the NGRTG that will follow it and unlike the MMRTG) was designed to operate in vacuum-only environments [10]. Given the design of the NGRTG and the lack of pressurized components or subsystems, it was assessed that the NGRTG did not require additional Micrometeoroids and Orbital Debris (MMOD) shielding. Furthermore, this RPS is well suited to the lunar surface thermal environment given the consistency of electrical power production across lunar night and lunar day; active cooling is not required. As a result, the NGRTG is the currently selected baseline RPS for the Endurance mission concept.

The MMRTG system is the only one of these RPS that is not in development or conceptual; it represents the current state of the art in sub-kW-scale space nuclear power systems and is currently in use on the NASA Perseverance Mars rover [10]. That said, the MMRTG is not well-suited to the lunar surface environment: multiple MMRTGs and active cooling are required to produce reasonable amounts of electrical power during lunar day. Additionally, the MMRTG design seals the thermoelectric modules within a pressurized environment; allowing the use of the MMRTG in a wide range of environments yet creating a single point of failure mechanism. As a result of this single point of failure, the MMRTG would require additional MMOD shielding for use in the lunar environment [10].

The Plutonium-based Stirling RPS is a potential future RPS concept that builds on advances in Stirling cycle energy conversion technologies. NASA is investigating these technologies because of their potential to increase the efficiency of converting heat into electrical power [10], enabling a reduction in the quantity of nuclear fuel required to achieve the same power level as an existing RPS. This RPS is moderately well-suited to the lunar surface environment; without active cooling, there is approximately 10% decrease in power production during the lunar day (the fins on the RPS do not shed enough heat for the RPS to operate within its optimal temperature regime). Given the design of the RPS and the use of Stirling converters (i.e., pressurized components), MMOD shielding would also be required to reduce the likelihood of catastrophic failure of key components of the RPS (however, it is likely that Stirling RPS do not have as high an MMOD-related risk as the MMRTG [10]).

The Americium-based Stirling RPS is a potential future RPS that builds on the development of the Plutonium Oxide-based Stirling RPS. This RPS is moderately well-suited to the lunar surface environment; without active cooling, there is approximately 20% decrease in power production during the lunar day (the fins on the RPS do not shed enough heat for the RPS to operate within its optimal temperature regime). One of the primary distinctions between this RPS and the rest is the fuel type: Americium, while having a lower thermal-power specific mass, is much more broadly available to acquire and has a much lower degradation rate (Am-241 half-life is 432 years, while Pu-238 half-life is 87.7 years). Using Americium as a fuel source for RPS in space missions is still in the early concept development phase. As with the Plutonium-based Stirling RPS, the Americium variant would require MMOD shielding. [11]

Table 3 provides a summary of the Mass Growth Allowance (MGA) [12] postures assumed for each of the RPS products.

Table 3. Summary table showing the MGA assumptions implemented for each RPS.

RPS	MGA (%)	Rationale
NGRTG	10%	In development with new suppliers and materials sources, based on heritage design.
MMRTG	0%	Existing product with known mass properties.
Stirling RPS (Pu)	20%	To accommodate TBD structural elements (brackets, fittings, etc.).
Stirling RPS (Am)	40%	To accommodate TBD structural elements (brackets, fittings, etc.). Americium heat source in concept design phase.

A summary of the RPS inputs that were used for the Team-X study are included in Appendix A.

The Thermal Subsystem Architecture Axis

The role of the rover's thermal subsystem is to manage and regulate the temperatures of the rover's components and instruments. This is done by dissipating heat in local regions characterized by an excess of stored thermal energy and retaining or generating heat in regions of insufficient stored thermal energy. The architecture of the thermal subsystem was a variable in the option-space for this study; the two thermal architectures were: A) using electrical heaters to control to generate heat for components outside of the warm central chassis, or B) using a waste-heat capture fluid loop (assumed to be a two-phase mechanically pumped fluid loop) to provide heat to those same components.

When using active cooling (option B), excess heat is typically rejected in the direction of the mobility system and rover arm using radiators on the front of the rover chassis. When using electrical heaters (option A), these are the same subsystems that require additional heat.

All point-design cases included radiators; these were assumed to be coated in a layer of dust over Z93 paint. If necessary, some point-designs included high-temperature front radiators. The assumed optical properties of the RPS varied: NGRTG was coated in black paint (impact of dust was not assessed), the MMRTG was coated in white paint and a monolayer of dust, and both Stirling RPS were coated in dust-free Z93 for the fins and main cylinder (while the Stirling converters were coated in black paint to account for dust). The time available for Team-X to evaluate these point-designs was constrained, so not all system level challenges could be exhaustively explored.

Team-X Implementation

The Team-X study used the latest version of the Endurance mission concept as a reference. For the scope of the Team-X study, only the design of the rover and the lunar surface mission were considered (launch services, CLPS, and astronaut interactions were not considered). When implemented into the Team-X concurrent design tool suite, all the rover's subsystems were modeled; the following subsystems could be kept constant across all studied cases: attitude control subsystem, instruments, command & data subsystem, telecom, and manipulation systems/mechanisms.

The ConOps was also implemented into the Team-X suite of tools. Most of the input assumptions for the ConOps model were kept constant across all rover cases; these ConOps model constants were the total traverse distance (2,000 km), the defined rover traverse speed (1 km/hour), commissioning & rendezvous, sampling, fault margin, and systems margin. The ConOps was iteratively evaluated for each rover point-design case; each iteration represents a variation in the charge time, battery mass, warm-up duration, and mobility actuator power to meet performance levels dictated by the change in the allowable mass of the rover. As the allowable mass of the rover increases, the mission duration cyclically increases given the increased rover performance needs

The Team-X tools converge each of the point-design cases starting with the rover mass properties, which are then used to calculate the power demands for mobility and size the power system. The power system sizing process includes ensuring that there is sufficient energy storage capability (using a secondary battery) for the most demanding 2-km drive scenario. Once the power system is sized, the mass properties are updated and the whole sizing process loops until convergence is achieved.

4. RESULTS

At the highest level, any of the four RPS products could yield a rover point-design capable of meeting the mission concept requirement of a 2,000 km traverse within a four-year period. The best performing RPS products were the NGRTG (for the higher power availability and increased suitability for the lunar surface thermal environment) and the Plutonium-based Stirling RPS (for the excess of power available).

Similarly, viable mission concepts could be achieved with either of the two thermal subsystem architectures; however, the pairing of RPS and thermal subsystem architectures could yield some variation in performance. To compare the cases against each other, two key figures of merit were defined: mission duration and allowable mass.

Mission Duration

The mission duration is a key figure of merit for this study because it represents variation in the operations cost of the mission, i.e., a shorter mission will have a lower cost and return samples more quickly. Thus, the mission duration figure of merit captures the temporal benefit or detriment of each decision in the option-space and averages that impact over course of the full duration of the mission. Mission duration was further broken down into three sub-categories: unmargined drive duration, mission duration including statistical faults, and margined mission duration.

Allowable Mass

The allowable mass [12] of the rover is a second figure of merit since it is representative of the cost of developing the mission concept (i.e., more mass, more money) and could also be used to understand mission feasibility (e.g., payload too heavy to deliver to the lunar surface).

Design Summaries for the Studied Cases

High-level summaries for each of the studied point-designs are provided below; additionally, Table 4 summarizes the key benefits and issues with each of the point-design cases. Table 5 summarizes key study results for all point-designs (in terms of mission duration and allowable mass).

Case 1A—The latest version of the Endurance rover design (as of June 2024) is equivalent to this case; it incorporates one NGRTG and uses electric heaters in its thermal subsystem. No additional MMOD shielding was required for the integrated NGRTG.

Case 1B—Similar to Case 1A, this variant of the rover utilizes a single NGRTG and a waste heat capture fluid loop. No additional MMOD shielding was required for the integrated NGRTG.

Case 2A—This case would represent a rover that uses MMRTG(s) and electrical heaters, but due to the RPS needing active cooling to produce reasonable amounts of electrical power during lunar day, this point-design case was omitted from consideration in the Team-X study.

Case 2B— This case represents a rover that uses two MMRTGs and a waste heat capture fluid loop. This case requires active cooling and two MMRTGs to produce reasonable amounts of electrical power during lunar day. Given the need for two MMRTGs, a collinear configuration was selected over a "V" configuration to simplify RPS installation; the added benefit of a collinear configuration is that the exterior MMRTG protects the interior MMRTG from Micrometeoroids and Orbital Debris (MMOD).

Case 3A— This rover case uses electric heaters and a single Plutonium Oxide-based version of a Stirling RPS. This point-design provides the second highest amount of power (there is an excess of power available; see "Excess Power Availability"). MMOD shielding is required to cover the Stirling converters that protrude from the RPS.

Case 3B— This rover case uses one Plutonium-based version of a Stirling RPS and a waste heat capture fluid loop. The performance of the RPS is enhanced by the addition of active cooling. This point-design provides the most power out of all the point-designs; (there is an excess of power available; see "Excess Power Availability").

Case 4A— The rover in this case uses one Americium-based version of a Stirling RPS and electric heaters. Power generation of the RPS is reduced due to the non-optimal thermal conditions on the rover and in the RPS. MMOD shielding is required to protect the Stirling converters.

Case 4B—The rover in this case uses a single Americium-based version of a Stirling RPS and a waste heat capture fluid

Table 4. Summary of key benefits and concerns with each point-design case.

Point-Design Cases	Benefits	Issues or Concerns
Option 1A *NGRTG w/ electric heaters*	• This is the lowest mass option	• 0.3-hour high power draw warmup preceding each 2 km night drive due to ~4-hour rover stops
Option 1B *NGRTG w/ fluid loop*	• Fluid loop removes need for night warmup mode • Fluid loop reduces charge mode power draw, making charging more efficient • Operationally robust because of active thermal control • Lowest mass fluid loop option • Short charge duration results in a fully margined mission duration near the minimum given study assumptions	• The reduced power draw gained from the fluid loop architecture costs ~50 kg (radiators, pumps, tubing, structural support, etc.) • Fluid loop increases complexity of design and integration
Option 2A *MMRTG w/ electric heaters*	• N/A	• N/A
Option 2B *MMRTG w/ fluid loop*	• Fluid loop removes need for night warmup • Fluid loop reduces charge mode power draw, making charging more efficient • Operationally robust because of active thermal control	• Elongated RPS structure blocks rear navigation cameras, complicating autonomy and configuration • Additional radiators should be studied for constraints on driving operations • Low RPS power availability increases mission duration • Combination of two MMRTGs, fluid loop and associated structure results in the highest mass option
Option 3A *Stirling RPS (Pu) w/ electric heaters*	• High power availability results in a smaller energy deficit and short charge durations • Short charge durations result in a mission duration near the minimum duration given study assumptions	• 0.15-hour warmup preceding each 2 km night drive due to ~1-hour rover stops • Electric heaters power draw requires short (<0.5-hour) charge mode • Lack of RPS thermal control results in a suboptimal operating temperature and power generation
Option 3B *Stirling RPS (Pu) w/ fluid loop*	• This point-design provides the most power out of all the point-designs • Fluid loop and high-power availability removes need for charge mode and night warm up • Operationally robust because of active thermal control and no charge modes • Removal of charge modes results in the minimum mission duration given study assumptions • Fluid loop thermal control allows RPS to be run at optimal temperature for power generation	• More massive RPS, fluid loop, and associated structure leads to a higher mass rover • RPS radiator structure blocks rear navigation cameras, complicating autonomy and configuration • Additional radiators should be studied for constraints on driving operations
Option 4A *Stirling RPS (Am) w/ electric heaters*	• Lower decay rate results in consistent charge durations between BOM and EOM	• 0.45-hour warmup preceding each 2 km night drive due to ~6-hour rover stops • The Stirling RPS runs at a preferable temperature during night, but runs hot during the day resulting in suboptimal power generation during the Lunar day • Low power generation, long Lunar day charge times, and higher mass result in a mission duration greater than the required 4 years.
Option 4B *Stirling RPS (Am) w/ fluid loop*	• Fluid loop removes need for night warmup and reduces charge mode power draw, making charging more efficient • Fluid loop thermal control allows RPS to be run at optimal temperature for power generation during Lunar day and night • Cooling of RPS allows higher power production during Lunar day, which allows this option to complete the mission within the 4-year requirement • Operationally robust because of active thermal control	• Additional front radiators should be studied for constraints on driving operations • Low power generation results in a long mission duration • More massive RPS, fluid loop, battery to support long charge time, and associated structural mass result in high mass rover

loop. The performance of this RPS is non-optimal due to the thermal conditions on the rover and in the RPS; some of the impact is mitigated by the rover's active cooling. MMOD shielding is required to protect the Stirling converters.

Excess Power Availability

The primary drivers for the key mission duration metric are the mass of the rover and the power. These two are inextricably linked through the rover's mobility subsystem (i.e., decreasing the mass of the rover reduces the required mobility power, and vice versa). Each of the rover options had different performance characteristics in terms of allowable mass and power available. When paired with the ConOps model, changes in power level could result in variations in mission duration. There are, however, limits on how much of the power available is truly useful.

The lower bound on the useful power available could be calculated by gradually decreasing the power available until the mission duration becomes 6 years (equivalent to the minimum mission duration that a solar-powered version of the Endurance rover was estimated to achieve). The upper bound on the useful power available was defined as the power level at which the rover no longer needs to stop to charge. Between these two bounds, all additional power available delivers a shortened mission duration. Below the lower bound, solar power would potentially provide a shorter mission duration. Above the upper bound, mission duration doesn't depend on power production. "Excess" power is available; any of this excess could be used for additional science (if funding is available for increasing the scope of the Endurance rover mission).

To evaluate each of the rover cases, four different traverse scenarios were evaluated: day traverse at beginning-of-mission (BOM), night traverse at BOM, day traverse at end-of-mission (EOM), and night traverse at EOM. It was found that Cases 3A and 3B, which used the Plutonium-based Stirling RPS, yielded excess power available. Case 3B has excess power available across all four scenarios, and Case 3A

Table 5. Summary of key study results. Green and red font colors denote the lowest and highest cases (respectively) for a certain metric (represented in a column).

Point-Design Cases	Allowable Mass (kg)	Unmargined Drive Duration (years)	Mission Duration including Statistical Faults (years)	Margined Mission Duration (years)
Option 1A *NGRTG w/ electric heaters*	590	1.33	2.6	3.5
Option 1B *NGRTG w/ fluid loop*	641	1.26	2.5	3.4
Option 2A *MMRTG w/ electric heaters*	N/A	N/A	N/A	N/A
Option 2B *MMRTGs w/ fluid loop*	817	1.64	2.9	3.9
Option 3A *Stirling RPS (Pu) w/ electric heaters*	639	1.0	2.4	3.3
Option 3B *Stirling RPS (Pu) w/ fluid loop*	701	0.97	2.4	3.3
Option 4A *Stirling RPS (Am) w/ electric heaters*	757	1.9	3.2	4.3
Option 4B *Stirling RPS (Am) w/ fluid loop*	789	1.73	3.0	4.0
	In reference to [12], this value is representative of an allowable mass.	This measure only includes the drive operations needed to accomplish the traverse (ignores time for sampling, commissioning or rendezvous with the astronauts).	This measure includes all components of the mission aside from the System Margin. This captures a comparison of the expected total mission duration for the design options. The value is representative of a predicted mission duration.	Includes all components of the mission with an applied system margin to capture unexpected slowdowns or "unknown unknowns". The value is representative of an allowable mission duration.

has excess power available across all scenarios except the EOM day traverse scenario. The extent of the excess power available ranges from +1% to +14% relative to the upper bound of power available. For all other cases, increased power production from the RPS would shorten mission duration. There were no cases where RPS power production was below the lower bound. Table 6 shows the power bounds for all rover cases.

5. SUMMARY

In the final analysis, we have seen that the differences in RPS product characteristics lead to differences in performance when applied to a rover operating on the lunar surface. While all the RPS product options could enable a lunar surface rover mission like the Endurance mission concept, some are better suited to the task.

The MMRTG is notably better suited for the atmospheric conditions of Mars than the comparatively harsh environment of the lunar surface; the thermal fluctuations across the day-night cycle and the increased MMOD-induced failure risk are key disadvantages. For the Endurance rover mission concept, the need for multiple MMRTGs to meet power demands is another disadvantage given cost considerations and configurational challenges.

The two Stirling RPS share similar advantages and disadvantages: they generally demonstrate potential efficiency gains on the MMRTG (reducing the amount of Plutonium needed, or altogether bypassing Plutonium in favor of the much more available Americium), yet the lunar surface thermal environment would not enable these systems to operate at optimal temperatures. There is still the matter of a moderate MMOD-induced failure risk (unless mitigated with non-zero mass shielding) and the relatively high mass. Notably for the Plutonium RPS, while in a non-optimal thermal regime, it was found to generate an excess of electrical power for the Endurance rover mission concept; this indicates that a higher-power rover mission concept in a different thermal environment might produce a more suitable RPS to mission/rover pairing. A potential solution for this rover mission concept could be to reduce the mass and power level of Plutonium-based Stirling RPS to better match the Endurance rover needs. Furthermore, Stirling RPS are untested in the lunar environment and still conceptual designs.

The remaining RPS was the Next Gen RTG, which provided the rover with balance: enough power at a low enough mass, the ability to operate well under lunar surface thermal conditions, and no need for MMOD shielding. While this

Table 6. Summary of useful rover power available analysis. Green font indicates that there is excess power available.

Point-Design Cases	Traverse Scenario	Rover Power Available (W_e)	Minimum Useful Power Available (W_e)	Maximum Useful Power Available (W_e)
Option 1A *NGRTG w/ electric heaters*	BOM Day/Night	231	131	296
	EOM Day/Night	214		
Option 1B *NGRTG w/ fluid loop*	BOM Day/Night	231	111	305
	EOM Day/Night	214		
Option 2A *MMRTG w/ electric heaters*	N/A	N/A	N/A	N/A
Option 2B *MMRTGs w/ fluid loop*	BOM Day/Night	209	116	327
	EOM Day/Night	179		
Option 3A *Stirling RPS (Pu) w/ electric heaters*	BOM Day	304	131	301
	BOM Night	342		
	EOM Day	291		
	EOM Night	339		
Option 3B *Stirling RPS (Pu) w/ fluid loop*	BOM Day	331	113	311
	BOM Night	342		
	EOM Day	317		
	EOM Night	328		
Option 4A *Stirling RPS (Am) w/ electric heaters*	BOM Day	168	157	311
	BOM Night	207		
	EOM Day	167		
	EOM Night	205		
Option 4B *Stirling RPS (Am) w/ fluid loop*	BOM Day	178	123	318
	BOM Night	184		
	EOM Day	176		
	EOM Night	183		

RPS is also untested in the lunar surface environment, it is based on proven heritage RPS.

From a thermal subsystem architecture standpoint, the key issues for the lunar surface are staying cool during the day and warm during the night. Given the RPS heat source, staying warm during the night was less of a concern than staying cool during the day. For an RPS on the lunar surface, the ability to shed excess heat could be critical.

Team-X, on completion of the study, noted that taking advantage of the waste heat from the RPS with a fluid loop to replace the need for electric heaters could be beneficial. In all studied cases, this change reduces the total mission duration (improving the margin on the four-year duration requirement); however, comes at the cost of additional mass. Whether or not the mass increase could be handled by a CLPS lander was outside the scope of this study, given the expanding number of conceptual CLPS lander options.

APPENDICES

A. RPS PRODUCT PARAMETERS

Table 7 includes a summary of the key RPS product parameters used throughout this study.

Note that both the Plutonium and Americium variants of the Stirling RPS make use of Multi-layer Insulation (MLI) instead of the solid insulation used in the Phase 1 design study for the Dynamic RPS (DRPS) conducted by Aerojet Rocketdyne.

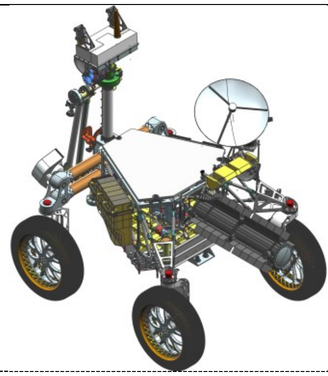
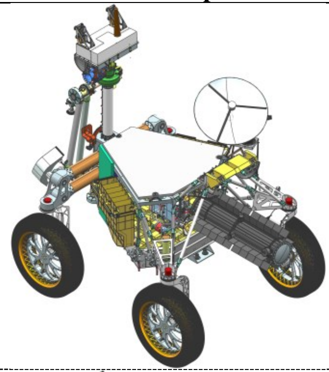
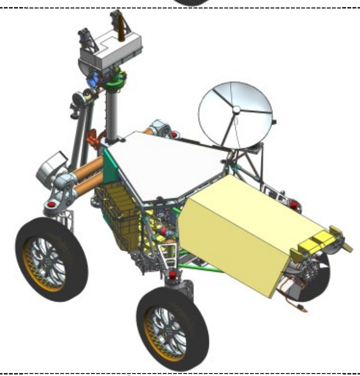
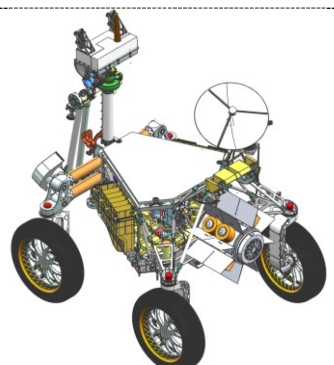
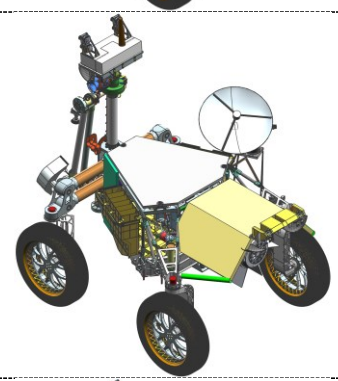
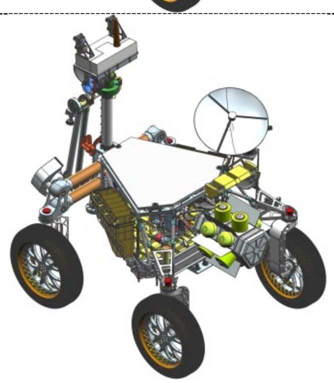
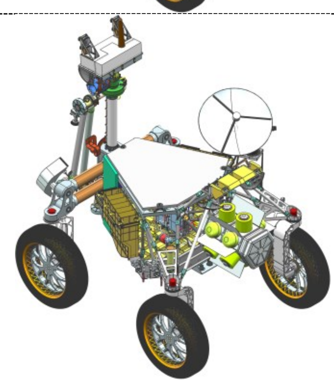
Table 7. Summary of key RPS Product Parameters.

Key System Parameters	MMRTG	NGRTG	Stirling RPS (Pu)	Stirling RPS (Am)
Estimated Launch Date Availability	Now	2030	2031	2031
# of GPHSs (# of converters)	8	16	6 (8)	4 (6)
Mass (kg) (including AC/DC controllers)	44	56	89.6	101
Mass Growth Allowance [12], assumed (%)	0%	10%	20%	40%
Design Life (years)	17	17	17	17
Max. Fueled Storage Duration (years)	3	3	3	3
Power, BOL (W_e, DC)	124	245	356	205
Degradation Rate (%/year) – electrical power	3.8%	1.9%	1.04%	0.17%
Power, BOL (W_t)	2000	4000	1500	800
Degradation Rate (%/year) – thermal power	0.8%	0.8%	0.8%	0.16%
Waste Heat, BOL (W_t)	1876	3755	1117	574
Operating Voltage, allowable (V)	22 – 34	22 – 36	22 – 36	22 – 36
Dimensions/CAD model *Including geometric details about thermal interfaces, fins, etc.*	Height of Gen. = 66 cm Diameter with fins = 64 cm	Height of Gen. = 114 cm Diameter with fins = 42 cm	Height of Gen. = 52.12 cm Diameter with fins = 77 cm	Height of Gen. = 62 cm Diameter with fins = 65 cm
Max. Allowable Flight Temperature (°K) *Including the reference measurement location*	485 (at fin root/rejector)	497 (at fin root/rejector) (-85° latitude with 0° azimuth)	448 (at Stirling engine/housing interface)	448 (at Stirling engine/housing interface)
Constraints on Operating Environment & Interfaces ➢ *Thermal* ➢ *Vibration* ➢ *Radiation* ➢ *Etc.*	Thermal Interface: Fins/Housing and/or Cooling Tubes Vibration: none	Thermal Interface: Fins/Housing and/or Cooling Tubes Vibration: none	Thermal Interface: Fins/Housing and/or Cooling Tubes Vibration: <10 N @ 100 Hz AC/DC Controller Efficiency: 93%	Thermal Interface: Fins/Housing and/or Cooling Tubes Vibration: <10 N @ 100 Hz AC/DC Controller Efficiency: 93%

B. Visual Representations of the Cases

Table 8 includes a set of visual representations of the seven evaluated point-design cases.

Table 8. High-Level Visual Representations of the studied Point-Design Cases.

	A. Electric Heaters	B. Waste-heat Capture Fluid Loop
1. NGRTG		
2. MMRTG	N/A	
3. Stirling RPS (Pu)		
4. Stirling RPS (Am)		

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Pre-decisional information for planning and discussion purposes only.

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