COMMERCIAL RADIOISOTOPE POWER SYSTEMS FOR SPACE RESOURCES MISSIONS.

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Introduction: Energy supply – both electric and thermal – is a foundational commodity for envisioned space resource activities. Dependence on solar power alone limits feasible space mining locations, operational up-time, and even economic feasibility. Radioisotope power systems (RPS) have an established record as an enabling technology for space missions [1]. Utilizing decay of radioactive isotopes, RPS provide heat to ensure survival in challenging thermal conditions and electricity to enable operations independent of solar power. Plutonium-238 (Pu-238) RPS units have powered Martian rovers, lunar surface missions, and spacecraft. Additional radioisotopes enable the industry to meet the surging demand for these systems, particularly for the cislunar missions. Historically, RPS have been exclusively fabricated and procured through government programs. However, recent innovations unlock commercial fabrication, offering commercially affordable options tailored for commercial markets [2]. These new systems can be widely available and affordable for space resources missions, with the first units reaching market in the 2020s. However, there is limited literature or academic analysis on how RPS technology benefits space resources activities if it were widely available. For example, the Commercial Lunar Propellant Architecture study only examined Pu-238 systems for high-power applications, not across distributed operations and mine lifecycle phases [3].

This study provides three contributions: it provides an update on recent developments in commercial RPS technology that make them available and affordable for space resource applications for the first time; it identifies operating environments relevant for space mining where RPS can be advantageous or essential for planned mining operations; it classifies specific space resource operations across a mine's lifecycle where RPS can prove beneficial or essential.

Commercial RPS: The last decade saw a rapid increase in commercial nuclear innovators, driven by the social need for carbon-free energy and capabilities that only nuclear energy can provide. Supported by numerous government programs and an influx of private capital, there are now dozens of companies developing nuclear technologies, with many focused on space applications.

Commercial RPS technologies are generally enabled using alternative radioisotopes, such as strontium-90 or americium-241 [2]. The technology can provide 10's of watts of electricity, which then can be scaled up to a kilowatt of electricity. These additional radioisotopes complement Pu-238 RPS mission sets where exceptionally high reliability is required.

Recent news and contracts underscore the potential of the technology as documented in [4]. Zeno Power demonstrated a Sr-90 fueled nuclear prototype in 2023 and secured radiological fuel and facilities to support spaceflights starting in 2026. The Department of Defense and NASA are turning to commercial companies to provide additional RPSs to enable capabilities required for continued American leadership in space. In addition to NASA Innovative Advanced Concept (NIAC) awards and other innovation grants, the government has recently awarded large contracts for RPS development. DOD has the LENS and JETSON project to develop RPS for satellites. In 2023, NASA awarded a Tipping Point to Zeno Power, in partnership with Intuitive Machines and Blue Origin, to design an americium-241 RPS to enable landers to survive the lunar night.

Lunar Night and Permanently Shadowed Regions: Many space resources missions are targeting resources where solar resources are limited, challenging, or even non-existent. The lunar day-night cycle means most of the Moon sees lunar nights that last for two Earth weeks, bringing extreme cold temperatures that damage spacecraft [5]. Permanently shadowed regions (PSRs), the primary targets for lunar water ice mining, are permanently dark and cold. Hence, absent available RPS technology, scientific investigations have been limited to geographic areas with "Peaks of Eternal Light," which promise sufficient solar most of the time [6]. The Volatiles Investigating Polar Exploration Rover (VIPER) mission provides a good example – its operations are limited by its reliance on solar and it plans to run from shadows and find safe havens on local peaks to survive even brief polar nights [7]. Such challenges limit access to mining sites.

RPS Applications for Space Resources: Abundant and affordable RPS can facilitate all elements and phases of space resources operation [8]. Thermal power, whether in a radioisotope heater unit (RHU) or byproduct from a RPS generator, can enable lunar night survival. Modular sizing can enable survival for everything from a payload or individual rovers to large, complex processing or storage equipment.

The most near-term space resources activities are focused on lunar ground prospecting, particularly for water ice. Prospecting rovers with RHUs can conduct long-duration missions and characterize large resource fields across the lunar surface. RHUs also enable long-term operations for infrastructure nodes, such as the communications and navigation infrastructure that is needed to facilitate precision and repeat landing.

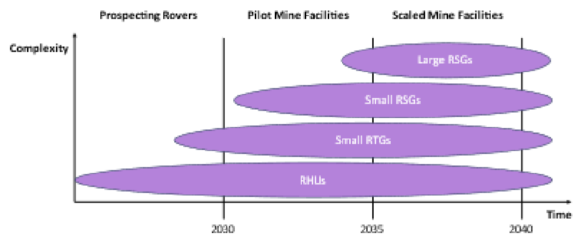

Figure 1. Applications Enabled by RPS

Pilot space mines will follow prospecting, often focused on testing individual equipment. A good example is MOXIE, the hosted payload on the Mars rover *Perseverance* that produced oxygen from carbon dioxide in the Mars atmosphere [9]. Perseverance (and hence MOXIE) was powered by a Pu-238 RPS. Similar near-term technology demonstrations can use commercial RPS. Another proposed example is radioisotope thermal mining is described in [10].

As space mining approaches industrial scales, RPS utility scales accordingly. Even though industrial facilities will require dozens of kilowatts to single digit megawatts, the distributed nature of operations will require heat and power across the architecture. Individual rovers can use RHUs for lunar night survival and to conduct limited PSR operations; with radioisotope thermoelectric generators (RTGs) and radioisotope thermoelectric generators (RSGs) they can traverse deep into PSRs to target the highest value deposits (such as carbon-bearing ices). RPS heat can support complex elements such as processing, transport, and volatile storage. RPSs can ensure distributed nodes, such as navigation or communications beacons across a site, can operate independently. RPSs can also ensure black start capabilities for complex, high-value technology, such as a nuclear reactor. The progressive development and use of commercial RPS, including associated technologies and regulatory pathways, can provide a foundation for lunar surface fission reactors.

Importantly, RPSs complement solar power to enable mission longevity and endurance, and they expand the range of energy options. Across space resources, a diversity of energy supply is essential to maximizing reliability while minimizing cost. Combining RPS with solar and storage technologies can bring ideal performance, from the smallest rover to the largest space mine.

Conclusion: The price of lunar landing and operations must be drastically reduced to realize a sustainable ISRU industry on the Moon. The CLPS program has reduced lunar landing cost to approximately \$100 million. This still represents \$7 million per day for a two-week mission. The ability to extend operations through the lunar night and reach design lives of five years will reduce the cost of operations to \$50,000 per day while maximizing value of the scientific instruments. Survival of the lunar night means the beginning of economically viable lunar industries.

Ultimately, prevalent use of RPS technologies can upend existing paradigms of space resources exploration and development. By transcending the sole reliance on solar energy, numerous advantages emerge, including enhanced flexibility in site selection, diminished risk to assets through diversified and modular architectures, and the capacity to target the most valuable resource deposits, regardless of their location. On the Moon, the peaks of eternal light would no longer be an operational necessity for lunar ice mining – transforming them from a prerequisite to a mere economic convenience. Both the number of accessible PSRs and the range of accessible locations in those PSRs would increase considerably, perhaps by an order of magnitude or more. Radioisotope power emerges as a foundational catalyst, enabling resource utilization this decade while reducing the future cost of sustainable mining operations on the Moon.

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