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In 2024, NASA's Space Technology Mission Directorate issued its inaugural Civil Space Shortfall Ranking found that the number one priority for the civil space sector was "survive and operate through the lunar night." Lunar environmental conditions impose extreme survival challenges for robotic and crewed space systems, with the thermal cycle being one of the most formidable engineering constraints. During the two-week-long lunar night, temperatures on the lunar surface drop -180C, and it can rise to as high as 120C during the two-week-long day. Recent lander missions, including Chandrayaan-3, SLIM, IM-1, IM-2, and Blue Ghost-1 all failed due to lunar cold temperatures.

This paper provides three major contributions to the night survival problem. First, it characterizes the environmental and operational challenges of lunar night survival for modern lunar missions. Second, it analyzes all landed missions historically to identify surface operations duration and technology approaches for surviving the lunar night, finding radioisotopes are the only demonstrated technology for long-duration missions. Third, the paper provides an initial quantification of the economic benefits of surviving lunar night, both for individual missions and based on a metric of cost per data return.

**Shadow and Ice: Lunar Night**

Unlike Earth, the Moon has no atmosphere to diffuse sunlight, resulting in starkly contrasting solar conditions. In equatorial regions, the lunar day lasts approximately 14 Earth days, with uninterrupted sunlight providing high power generation potential for solar-based systems. However, the subsequent 14-day lunar night presents a critical challenge, as solar-dependent systems must either store enough energy to survive or incorporate additional power sources such as radioisotope-based systems. The environment on the Moon is not solely a macro-climate – it varies by latitude because of solar incidence/duration and terrain-shadowed microclimates exist across the entire surface. The Moon's poles, particularly permanently shadowed regions (PSRs), experience even more extreme insolation variations, making long-duration solar power even less viable. Materials must be engineered to withstand repeated thermal cycling without degradation, without the radiative cooling and convective heat transfer.

Electronics have traditionally been designed for the Earth environment. It is very difficult to design electrical systems capable of surviving temperatures that vary as much as 300C. Since power is generated during the day, most designs focused on conditions during lunar daytime – leading these designs to malfunction or break during the cold lunar night.

- **Electronics**: Extreme temperatures cause materials in the spacecraft to contract and expand unevenly, which can break circuit boards, wires, soldered joints, or other vital components. Electrical resistivity decreases, meaning components become unstable in terms of voltage regulation. [1]
- **Batteries**: Battery cases can crack open due to differences in coefficients of thermal expansion (CTE). Liquid electrolyte solutions are prone to freezing for standard lithium-ion batteries, and this can change the chemical structure of the solution even after it melts. This can also cause the battery to discharge to unhealthy levels for long periods of time before being able to be recharged.[2]
- **Solar Panels**: Solar panels can delaminate due CTE differences in the materials in the solar panel. **Material Properties**: Specific heat decreases at low temperatures. Thermal conductivity increases for pure metals, ceramics, and silicon, but decreases for metal alloys at low temperatures. Electrical Resistivity of metals decreases at low temperatures, leading to lack of voltage regulation and increasing chance of shorts.[3] Semiconductors lose free charge carriers at low temperatures, which causes them to behave as insulators.[4]

[1] https://cds.cern.ch/record/1973682/files/arXiv:1501.07100.pdf
[2] https://www.sciencedirect.com/science/article/abs/pii/S0378775315303153
[3] https://ntrs.nasa.gov/api/citations/20040001034/downloads/20040001034.pdf
[4] https://matse1.matse.illinois.edu/sc/prin.html#:~:text=But%20at%20low%20temperatures%2C%20intrinsic,electrons%20in%20the%20conduction%20band.

Operationally, these challenges mean lunar missions without survive the night capability are limited in available sites, constrained to narrow launch and landing windows, and unable to target areas of greatest scientific or resource interest. Communication limitations due to the lunar terrain and Earth's rotation further narrow available sites.

### Spacecraft Survival Strategies and Radioisotope Power

The lunar night presents a significant challenge for long-duration surface operations, but it is not insurmountable. Of the 31 successful soft landings on the Moon, 17 missions have survived their first lunar night, demonstrating that various strategies can enable survival. There are two primary approaches:

- **Solar + Storage Missions**: Six missions, including NASA's uncrewed Surveyor landers in the 1960s, demonstrated that heat generation via stored solar energy can extend mission life. However, these missions averaged only 3.8 lunar nights before failure, with significant degradation along the way.
- **Radioisotope-Powered Missions**: Eleven missions, including the ALSEP (Apollo Lunar Surface Experiments Package) stations, Soviet Lunokhod rovers, and Chinese Chang'e landers, utilized RHUs and RTGs to sustain operations. These missions consistently outperformed solar-reliant counterparts, with ALSEPs and Chang'e missions surviving for tens of lunar nights, often being decommissioned due to program constraints rather than hardware failure.

Maintaining an optimal thermal environment has been the most effective approach to surviving the lunar night. Solar power with energy storage has been used but brings significant mass penalties due to additional batteries required, and parasitic loads needed to keep them warm. Even if solar and storage challenges can be mitigated, this method does not support operation in permanently shadowed regions (PSRs) or provide continuous nighttime power.

The only proven long-term solution for survival and operation is the use of radioisotope heater units (RHUs) and radioisotope thermoelectric generators (RTGs). While Pu-238-powered RTGs have been historically expensive, alternative isotopes offer a significant reduction in cost, making radioisotope power systems (RPS) more viable for lunar infrastructure at scale. The progression from RHUs to RTGs and radioisotope Stirling generators (RSGs) provides a direct pathway to long-duration lunar night survival and operational capabilities in PSRs, while also de-risking fission surface power technologies.

### Economic Benefits of Night Survival

Spending $100 million on a lunar lander that can only last one lunar day is like building an expendable launch vehicle – it does not enable economies of scale that unlock growth in a sector. The cost of returning data from the lunar surface has historically been high, making mission longevity a critical factor in improving efficiency. For example:

- Surveyor missions in the 1960s returned data on the order of $10,000 per megabyte.
- Firefly's Blue Ghost Mission-1 in 2025 is estimated to have returned data at $1,000s per megabyte.
- Radioisotope power systems (RPSs) could reduce the cost of data return to tens of dollars per megabyte.

By extending mission duration beyond a single lunar day, STN technologies provide a dramatic improvement in the cost-effectiveness of lunar science and ISRU prospecting efforts.

### STN and ISRU Need RPS

Surviving the lunar night is not just a technological challenge—it is a fundamental requirement for long-term lunar operations, scientific exploration, and resource utilization. STN technologies, particularly RPSs, are mission enablers for future ISRU operations. Many ISRU site-selection efforts will have only one opportunity to validate a location. Assuming all critical objectives can be completed in a single lunar day increases mission risk, as unforeseen challenges could force an early shutdown. STN capability significantly increases operational resilience, allowing for more sample collection, better site characterization, and a higher probability of success.

Historical mission data demonstrates that radioisotope power systems (RPS) are the only proven technology for sustained operations beyond a few lunar nights, providing a critical advantage over solar and storage solutions that face severe mass and energy limitations. As the lunar economy advances, missions will increasingly depend on long-duration infrastructure capable of continuous operation through extreme temperature cycles and in permanently shadowed regions. Investing in Survive the Night (STN) technologies today will de-risk future large-scale lunar missions, improve the cost-effectiveness of ISRU prospecting, and enable the sustained presence necessary for long-term lunar development.