
# WORKSHOP REPORT

**July 2019**

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# Survive and Operate Through the Lunar Night

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**June 2019**

## EXECUTIVE SUMMARY AND RECOMMENDATIONS

The lunar day/night cycle, which at most locations on the Moon, includes fourteen Earth days of continuous sunlight followed by fourteen days of continuous darkness and extreme cold presents one of the most demanding environmental challenge that will be faced in the exploration of the solar system. Due to the lack of a moderating atmosphere, temperatures on the lunar surface can range from as high as +120 C during the day to as low as -180 C during the night. Permanently shadowed regions can be even colder. However, surviving and operating through the lunar night is critical to accomplishing key science and exploration objectives and lunar night operations are essential for a sustained presence on the Moon. Developing the capabilities needed for lunar night survival and operations will also help enable future operations in other thermally-extreme space environments, thus increasing our ability to explore and operate sustainably throughout the solar system.

Early Capabilities and Evolution: Initially, small payloads delivered on landers might be designed to survive lunar night and continue operations during subsequent days. Existing thermal and power system solutions should be able to support this. Likewise, incremental improvements in thermal control and power systems should make it possible for larger fixed payloads and rovers to at least hibernate through the night and then continue daytime operations. Mobility is essential for many science and exploration objectives and a long-range rover that hibernates during the night could be very productive. Further incremental improvements could enable a low-power nighttime operating mode. The introduction of more advanced technology solutions would eventually enable full day/night operations.

Distributed networks, in particular a geophysical network, would benefit from continuous operations from the beginning and since their power requirements might be very modest, early implementation is a realistic goal. Observations of volatiles and phenomena that occur during transitions at the terminator also need to operate at least for some portion of the night. Scientific exploration and resource prospecting in permanently shadowed areas presents similar thermal and power challenges, although strategies might be employed to limit the duration of operations within the extremely cold shadowed region.

Ultimately a power-rich environment will be necessary to enable the full range of science, exploration, and commercial activities envisioned for the Moon. These activities include globally-dispersed robotic exploration, people living and working on the surface, and the production of propellant and other commodities derived from lunar resources. A sustained lunar presence implies the need for permanent infrastructure on the Moon.

Energy Management: At least to some degree, thermal management technologies already exist to address the lunar night challenge. Insulating materials and innovative techniques can be applied to minimize heat loss. Lunar dust, which is usually viewed as a hazard, can be useful to increase absorptivity of surfaces and regolith could be used as an insulator or to create thermal shelters. The thermal wadi is a more advanced approach to using local material to create a thermal reservoir. The technology of thermal switches has been advanced as well as thermally-robust materials such as bulk metallic glass. Additional development of components and systems that are resistant to extreme cold, including solid state batteries, would be a beneficial technology investment.

In general, developing systems to survive or operate through the lunar night involves a system-level design process that integrates thermal management and power technology as well as innovative operational strategies. It is important to look to the lunar environment itself for some solutions. As mentioned above, lunar dust and regolith can be useful. The natural vacuum in all locations and the extreme cold experienced at night and in shadowed areas could be helpful in maintaining superconductors and other cryogenic systems at low temperatures with little or no additional power. The intense solar heating during the day may be useful as well as the potential to exploit large temperature differences between hot and cold such as with a thermo-electric generator. Some attention needs to be directed to the thermal modeling of conditions during dawn and dusk as well as the extreme heat of lunar noon.

Power Generation: With respect to power technologies, for low power operations, advanced batteries offer a viable option, especially if technology improvements result in lower mass and less thermal sensitivity. Low power robotic missions that require steady day and night power would benefit from currently-available 100 watt-class radioisotope generators. Larger robotic missions, in the kilowatt or multi-kilowatt range, could utilize advanced dynamic radioisotope systems or small fission power systems such as Kilopower. These offer the most mass-effective power solution for lunar night operations. The regulation of radioactive systems could potentially limit their availability for commercial ventures on the Moon.

In conjunction with solar arrays for daytime power, regenerative fuels cells provide the lowest mass, non-nuclear option to supply power during the lunar night, with the potential for using residual lander propellants or lunar-derived ice as a source for hydrogen and oxygen reactants. Batteries may be a viable option for energy storage, if sufficiently advanced in terms of performance, mass, and thermal robustness, There are also other novel but less mature technologies for storing energy for use during the night, such as superconducting electromagnetic coils.

Investments in development of these power technologies should continue with a focus on design suitability for lunar surface environments and an emphasis on testing. Near-term demonstrations on lunar landers could provide critical technology verification that would reduce the risk of their use in future human missions.

Power beaming as an energy source for surface operations offers scalability and the potential for power distribution across many lunar sites and rovers across the Moon. Power beaming systems can also incorporate communications links. Power beaming might be done globally from an orbiting satellite or locally between a power source and mobile assets. Although power beaming technology is not seen by some as very mature, due to its unique attributes, it warrants consideration for further technology development.

Regarding technology needs, it is recommended that NASA concentrate its efforts less on additional trade studies and more on building prototype systems and testing them in the lunar environment. The Commercial Lunar Payload Services (CLPS) program is intended to provide early and frequent access to the Moon for higher-risk, and potentially higher payoff missions. NASA should make full use of this program for technology demonstrations of capabilities to enable survival and operations through the lunar night.

<u>Certification and Standards</u>: It is recommended that NASA engage in a systematic effort to identify and certify avionics and other components for the extreme thermal environment of the lunar surface. A publicly-accessible database of such components would benefit everyone developing landers, rovers, instruments, and other systems for the Moon. Another database that would be helpful to technologists would be the power and thermal management requirements for the most common existing instruments that are under consideration for lunar missions.

There appears to be strong interest in the larger community for NASA to establish standards related to instrument and payload interfaces, communications, and power. It was noted that standards generally help lower the cost of doing business in a technical and commercial sense.

<u>Public and Private Services</u>: Further consideration needs to be given to the question of whether the government intends to provide power and communications as a service to other government and commercial users or to purchase power and communications services from commercial vendors. If the approach is for the government to purchase these services, there appears to be interest in the private sector to provide those services but it is critical that the needs be realistically appraised and that there be firm commitments to purchase the power and communications services at guaranteed levels. There may be interest from other nations in communications network operations and international cooperation can also contribute to maximizing scientific and commercial return.

Propellant produced from lunar resources is a commodity that might be provided by commercial vendors but again, there will need to be a relatively certain market and the government is likely to be the primary customer, at least at the beginning. Regarding the production of propellant, such ventures will rely on early resource prospecting results and governments may be the only entities with the means to perform the initial prospecting.

The report that follows provides a summary of the presentations and discussions among the nearly 200 participants at the workshop.  There are links to video recordings of the presentations and panel discussions.  There are also links to reference documents and the abstracts of each of the 29 poster session presentations.  This report is intended to provide a resource for those seeking information on these challenges and opportunities and also to serve as a starting point for further planning and implementation of efforts toward surviving and operating through the lunar night.

## WORKSHOP SUMMARY

### Workshop Purpose and Scope

The Survive and Operate Through the Lunar Night Workshop was held on November 13, 2018 at the Universities Space Research Association (USRA) Headquarters in Columbia, Maryland.  It was jointly sponsored by the NASA Science Mission Directorate (SMD), Human Exploration and Operations Mission Directorate (HEOMD), and Space Technology Mission Directorate (STMD) with support from the Solar System Exploration Research Virtual Institute (SSERVI), Lunar Exploration Analysis Group (LEAG), NASA Space Portal, and USRA.  The workshop organizing committee and participants are listed in Appendix A.

The one-day workshop was held to discuss the challenges and opportunities for surviving and potentially operating through the 14-day lunar night.  One of the key capabilities needed for performing long-duration missions on the lunar surface is survival, and ultimately operational viability, through the lunar night.  The ability to survive and operate through the lunar night is also relevant to operations in permanently shadowed areas of the Moon; areas of great interest for science and resource prospecting.  As NASA and commercial ventures plan for increasingly complex and capable science and exploration missions to the surface of the Moon, information was sought from the broader community on capabilities to enable these activities to be productive through multiple lunar day/night cycles.  Participants were welcomed from industry, academia, the lunar science community, and other government agencies.

### Background and Objectives

The primary technical challenges to surviving the lunar night are the lack of solar insolation for power and heating at night and the extreme temperature ranges (-180 C to +120 C) on the surface during the 28-day/night cycle.  Permanently shadowed regions can be even colder.  Most electronics and spacecraft subsystems can freeze and become unrecoverable at these extreme cold temperatures.  The workshop addressed mission opportunities, science needs, and technical challenges and provided a discussion forum to creatively seek solutions to meet the objectives for the near and long-term lunar surface missions of NASA, other agencies, and commercial industry. The workshop objectives included:

- Review the expected needs and opportunities for science, exploration and commercial operations on the Moon (with emphasis on early robotic activities) as they evolve from surviving the lunar night to operations throughout multiple day/night cycles.
- Review the current state-of-the-art for power generation, storage, and distribution (solar, nuclear, battery, beaming, etc.) and thermal management technologies for long-duration operations on the lunar surface.
- Present novel concepts for power and thermal management systems, design features, and operational techniques for maximizing survival and functionality of components and systems through the day/night cycle.
- Identify the gaps between mission needs and system capabilities for surviving and operating through multiple day/night cycles.
- Explore opportunities for public-private partnerships to develop sustainable capabilities for power and thermal management and the potential for commercial lunar infrastructure services.
- Summarize significant findings and recommendations in a workshop report for NASA decision-makers that includes a clear definition of the technology development needs and gaps and the most promising potential solutions, particularly for the earliest robotic mission applications.

**Workshop Agenda –** topic headings are hyperlinks to online recordings of workshop talks

| **Topics** | **Speakers** |
|---|---|
| Welcome and Workshop Objectives | Andrew Petro, NASA HQ<br>Renee Weber, NASA MSFC |
| Overview of Lunar Day/Night Environmental Conditions | Brett Denevi, Johns Hopkins University - Applied Physics Laboratory (JHU APL) |
| Lessons Learned from Missions that have Survived Lunar Night | Ron Creel, NASA retired |
| Science Perspective | Sam Lawrence, NASA JSC, LEAG |
| Exploration Perspective | Ben Bussey, NASA HQ |
| Panel Discussion: Evolving Requirements from Survival to Continuous Operations for Science, Exploration, and Commercial Activities | Greg Chavers, NASA HQ<br>Dave Blewett, JHU APL<br>Dana Hurley, JHU APL<br>James Carpenter, ESA |
| Panel Discussions: State of the Art, Potential Solutions, and Technology Gaps | |
| Power generation, storage and distribution | Moderator: Lee Mason, NASA STMD<br>Len Dudzinski, NASA HQ: RPS & fission<br>Bob Sievers, Teledyne: fuel cells, MMRTG<br>Erik Brandon, JPL: advanced batteries<br>Paul Alburtus, ARPA-E: energy storage |
| Thermal management systems, strategies, and component design features | Moderator: Rubik Sheth, NASA JSC<br>Eric Sunada, JPL: robotic missions<br>Chad Bower, Paragon: commercial systems<br>Kurt Sacksteder, NASA GRC: thermal wadi |

| | |
|---|---|
| Commercial Space Panel: Understanding the economic business case for creating lunar infrastructure services and lunar markets. | Moderator: Allison Zuniga, NASA ARC<br>George Sowers, Colorado School of Mines<br>Dennis Poulos, Poulos Air & Space, Inc.<br>Dennis Wingo, SkyCorp, Inc.<br>Mohamed Ragab, iSpace, Inc.<br>Rolf Erdmann, PT Scientists |
| International Space University Summer Project Presentation "Lunar Night Survival" | Matt Henderson and Ilaria Cinelli, ISU |
| Open Discussion | Co-chairs, All workshop participants |
| Poster Session | See Appendix B |

**Overview of Lunar Day/Night Environmental Conditions**

Brett Denevi, a lunar scientist at the Johns Hopkins University - Applied Physics Laboratory provided a briefing on the environmental conditions over the lunar day/night cycle.

The lunar surface is a unique environment with temperature, illumination, and plasma charging conditions that vary with time and location including the equatorial and mid-latitude regions, polar regions, and the terminator. Therefore, time and location are important factors in determining mission thermal management and power needs.

Temperature: The Diviner Lunar Radiometer Experiment (DLRE) on the Lunar Reconnaissance Orbiter (LRO) has provided detailed thermal maps of the Moon. The daytime maximum ranges from 387-397 K (114-124 C) while the nighttime minimum before sunrise can descend to 95K (-178 C). Areas above 60 degrees latitude have lower variations in temperature and rockier places tend to stay warmer longer. There are some small regions on the lunar surface with relatively temperate nights (similar to nights on Mars), these occur in small rocky craters with steep slopes. It should be noted that a potential benefit of the low temperature at night is the availability of passive cooing to cryogenic temperatures.

Illumination: In the mid-latitudes there are long periods without direct solar illumination, however on the near-side, earthshine is not insignificant. The effect of earthshine under the best conditions has been estimated to be equivalent to a 60-watt lightbulb, 6 feet overhead. Lyman-alpha and zodiacal light are other possible sources of light illumination.

The polar regions have the most extreme range of illumination. Although there are no literal "peaks of eternal light", there are locations which have illumination for up to 72% of the year. Illumination in the polar regions can increase with elevation above the surface. A solar panel two meters above surface, in certain locations, can have solar illumination for up to 86% of the year. Mobility can also provide for extended periods of illumination. For example, a rover traverse in a polar region could be designed to follow the light and remain illuminated for up to 94% of the year. In this example the average traverse speed would need to be 2.5 meters per hour with a maximum speed of 30 meters per hour and there would still be about 100 hours of eclipse during a year.

Plasma and Charging: The day side of the Moon is positively charged, while the night side is negatively charged. The terminator has a large potential difference over a short distance and therefore a strong electric field. This charging is not well characterized but could cause uneven charging of a spacecraft which raises concerns about charging and grounding. There may be electrostatic dust transport at the terminator but the evidence is not conclusive.

**Lessons Learned From Missions That Have Survived Lunar Night**

A briefing on lessons learned from past lunar missions was presented by Ron Creel, a retired NASA employee who worked at the Marshall Space Flight Center for many years. He had significant involvement, especially in thermal management, with the Lunar Roving Vehicle used on the Apollo 15, 16 and 17 missions.

Surveyor Missions: The US Surveyor landers were powered by solar arrays and batteries and were not specifically designed to survive the night. A summary of the operational experience with the successful Surveyor missions is provided below.

Surveyor I: provided excellent data for two consecutive lunar days and partial data were transmitted as late as the fifth and sixth lunar days. The spacecraft operated for 48 hours into the first lunar night.

Surveyor III: shut down 2 hours after sunset on the first lunar day

Surveyor V: operated for 115 hours into the first lunar night, it also experienced an eclipse by the Earth on the second lunar day, and operated for about 215 hours into the second lunar night. It operated for a short period of time during the fourth lunar day.

Surveyor VI: operated for about 40 hours into the first lunar night. It was revived on the second lunar day, but only provided thermal data for a short time.

Surveyor VII: operated for about 80 hours into the first lunar night and was successfully revived on the second lunar day, providing good thermal data during the day. However, contact with the spacecraft was lost before sunset on the second day.

ALSEP: The Apollo Lunar Surface Experiments Packages (ALSEPs), were immobile devices placed on the lunar surface at the Apollo 12, 14, 15, 16, 17 landing sites. They are the best examples, to date, of surviving and operating through lunar day-night cycles. They were powered by 70-Watt Plutonium-238 Radioisotope Thermoelectric Generators (RTGs). They all survived and operated through scores of lunar day-night cycles for several years. They were shutdown, only for budgetary reasons, on September 30, 1977. According to a chart presented by Ron Creel the ALSEP external temperature ranged from 80 C to -185 C over the day-night cycle and the corresponding internal temperature ranged from 80 C to -30 C. There was some evidence that lunar dust accumulation on the ALSEP packages contributed to increasing temperatures.

Apollo Rovers: The crew rovers used for Apollo 15, 16, and 17 were battery powered and were not intended for night survival or operation. The Apollo rovers had a mass of 218 kilograms and only 4.5 kilograms was devoted to thermal control. A significant thermal issue was dust accumulation on radiators but that concern was to avoid overheating during the day. Studies were done for a more advanced version of the rover (for later Apollo missions that were cancelled) that would have had a trailer with an RTG power source. That version of the rover might have had some night survival capability. More ambitious crew rovers for future human missions are expected to require multiple kilowatts of power for operation and therefore the lower-power RTG's used in the past are not expected to be adequate for that application.

Soviet Lunokhod Rovers: From 1970-1973, the Lunokhod 1 and 2 rovers, operated on the lunar surface by the Soviet Union hibernated through the lunar night but did not operate through it. Lunokhod 1 survived eleven lunar day-night cycles and Lunokhod 2 survived four day-night cycles. The Lunokhod 2 failure is attributed to operating difficulties which resulted in regolith being deposited on the radiator, leading to overheating during the day.

Proper construction and lubricants along with a heating system appear to have enabled this relative success. The heating system consisted of a radioactive polonium 210 source which heated air circulated through a pressurized chamber containing electronics, batteries, and instruments. The top of the rover had a large lid with solar arrays and a radiator which could be opened during daytime operations and closed at night. After hibernation, the Lunokhod rovers needed to wait to heat up for two days before moving in the lunar morning. The morning and late afternoon were the best periods for roving. During lunar noon, the rovers had to limit their movement because the high sun angle made it impossible to see surface features such as craters.

Chinese Yutu Rover: Limited information is available on the first Chinese lunar rover. It appears that the rover did not move after the first night but did continue to transmit data over multiple day-night cycles. It is believed to have radioisotope heater units.

## Science Perspective

Samuel Lawrence, the lead scientist for lunar exploration at the NASA Johnson Space Center and the Chair of the Lunar Exploration Analysis Group (LEAG), provided a talk on the Science Perspective.

Surviving and operating through lunar night is critical for accomplishing key science and exploration objectives. The discussion of science needs was based on several past studies including the LEAG Advancing Science of the Moon report (https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf) and the Lunar Exploration Roadmap (https://www.lpi.usra.edu/leag/roadmap/). Surviving and operating through the lunar night is a key capability in support of the Roadmap as six of the eleven science goals (listed below) require long term investigation and operation through the lunar night. Specifically, a continuously operating geophysical network is needed for the following objectives:

- Thickness of the crust and variability
- Stratification of the mantle
- Size, composition, and state of the lunar core

The ability to observe temporally-changing phenomena that might occur across the lunar day/night cycle is needed for the following objectives:

- Composition and distribution of polar volatiles
- Investigation of the lunar atmosphere
- Electrostatic transportation of dust

The 2017 Advancing Science of the Moon report (ASM-SAT) endorsed the findings and conclusions of the 2007 National Research Council Scientific Context for the Exploration of the Moon report. Several high-priority science objectives that have emerged more recently, based on the ASM report, are to understand the origin of the Moon, lunar tectonism and seismicity, and the lunar water cycle. Continuous operation through the lunar night would be important to each of these investigations.

In particular, science operations in polar regions, particularly in permanently shadowed regions, and through the passage of the terminator may rely on the capabilities encompassed by operating through the lunar night.

The crosscutting capability needs that derive from these lunar science objectives are:

- Long-lived rover capable of surviving the night
- A widely emplaced geophysical network and lunar exosphere observation stations capable of operating continuously through the day/night cycle

In addition, the Moon has been identified as a valuable location for astrophysics observatories and these types of facilities would require the capability to operate through the night.

Regarding technology, the Lunar Exploration Roadmap specifically calls for the development of fission power for the surface and for rechargeable power sources for fixed and mobile systems.

A lunar sample return mission is possible to accomplish within a single lunar day, however a longer duration mission for sample collection has the potential to be much more productive and would therefore benefit from night survival capability.

**Exploration Perspective**

Ben Bussey, from NASA Headquarters, Human Exploration and Operations Directorate provided a talk on the Exploration Perspective.

One frame of reference for understanding what we wish to learn prior to future human lunar exploration are the Strategic Knowledge Gaps (SKG's). The lunar SKG's can be grouped into three categories:

- Understanding lunar resource potential
- Understanding the lunar environment and its effects on human life
- Understanding how to live and work on the lunar surface

The SKG's should not be viewed as questions that must be answered before human missions to the Moon can begin but as a means to reduce risk and to allow for simpler and less costly design solutions.

The ability to address these SKG's will be enhanced by the capability to survive and operate through the night. Specifically, for understanding lunar resources, it will be necessary to operate in areas of temporary darkness as well as permanently shadowed regions to assess the presence and characteristics of volatiles. In the case of the other two categories, radiation, plasma, and dust are significant environmental factors and the ability to observe the environment in a persistent manner through multiple day/night cycles will be important. Furthermore, if there is a desire to maintain a human presence on the lunar surface for long durations, all of the engineering challenges of operating habitation, surface transportation, and other support systems reliably and continuously through multiple day/night cycles must be overcome.

**Evolving Requirements from Survival to Continuous Operations for Science, Exploration, and Commercial Activities**

For this discussion the panelists included Greg Chavers from NASA Headquarters, Human Exploration and Operations Directorate, Dave Blewett and Dana Hurley from the Johns Hopkins University – Applied Physics Laboratory, and James Carpenter from the European Space Agency.

<u>Early Missions:</u> For early commercial lunar lander missions, it is unlikely that the lander systems will provide any night survival services and therefore instrument packages should be designed to be self-supporting with respect to night survival. Instrument packages designed to capture and store the heat generated by the instruments themselves may be one feasible approach.

There is interest in establishing standard interfaces for payloads on landers and that would likely apply to general purpose rovers as well. Such a goal may be too ambitious for the earliest versions of the new commercial landers but this is a concept that should be pursued. Likewise, there is interest in defining a standard set of instruments that could be delivered on lander missions to multiple sites on the Moon. A standard set of instruments might include a magnetometer, solar wind detector, heat flow probe, and instruments to measure properties of dust.

There may be spacecraft and instrument components that are able to survive the temperature extremes of the lunar day-night cycle. However, aside from developing lunar systems, the motivation does not generally exist for component vendors to test and certify components for these conditions. It is costly for each individual lunar system developer to perform this testing themselves. An important contribution that NASA (or other independent entity) could make would be to test and certify components for the lunar environmental conditions and maintain a database of suitable components to share with the commercial and scientific community

Long-range roving capability will be required for science activities at all latitudes on the Moon. The ability to simply survive the lunar night is enabling for long-range rovers although night operation would be of value.

Instrument Networks: Geophysical measurement networks are a key science need that will also provide valuable knowledge to support exploration. The International Lunar Network (ILN) concept that was studied several years ago was intended to operate continuously, relying on solar arrays and batteries for storage. At the time of the study is was estimated that each unit would require well over 100 kilograms of batteries, which was a significant penalty but a feasible approach. With the latest battery technology, that energy storage mass could be reduced significantly.

Very small, low-cost, distributed networks are an attractive approach for lunar science and exploration. The technology challenge will be to develop small self-contained instrument packages that can survive and/or operate through the lunar night.

Lunar Volatiles and Resource Prospecting: An urgent need for sustained lunar exploration is to send rovers into permanently shadowed craters to characterize and quantify potential water resources.

The investigation of lunar volatiles (including but not limited to water ice) is a primary objective for science and for resource prospecting. There are two types of locations where these investigations would occur. In permanently shadowed regions it would be necessary for instruments and rover platforms to operate at least for short periods in the completely dark and extremely cold environment. It is also likely that robust mobility systems will be needed to carry instruments into the permanently shadowed regions. Outside of permanently shadowed regions, and at many locations on the Moon, there might also be volatiles deposited on the surface during lunar night. To investigate these locations would require at least some instrument operation for a period after sunset and prior to sunrise. Being able to operate through the day-night and night-day transition is necessary to observe phase changes, which would be important in understanding volatiles and also the lunar atmosphere.

In connection with the investigation of volatiles and the lunar atmosphere and their possible inter-relationship there is an important question about whether some of the potential water on the Moon might be a renewable resource. In other words, is there a "water cycle" (or other volatile cycle) on the Moon? This is a question that can be answered by making observations through the day-night transition periods.

Observations from a lander or stationary platform are likely to be sufficient to collect data on the lateral distribution of volatiles on the surface, within sight of the lander or platform.

To investigate the presence of volatiles below the surface, mobility in the form of a rover will be needed. This has important implications since the provision of night survival and/or operations capability for a rover may be more challenging than for a stationary platform. However, in the polar regions, mobility might become an advantage since a rover might re-locate itself periodically to take advantage of the extended lighting that can exist in specific polar locations. The key instruments for investigation of polar volatiles would be a neutron spectrometer and a mass spectrometer to measure samples from various depths.

Human Missions: Any human exploration missions that extend for more than seven days will need to meet extremely demanding thermal management requirements. Simply preserving operational surface infrastructure for use on multiple missions, even if the crew is not present through the night, will require careful engineering. To have a human crew living and working on the Moon through one or more day-night cycles is assumed to require a continuous multi-kilowatt power source. The known options for such a power source are a fission generator or a photovoltaic system with a very advanced capability for energy storage during the day and discharge at night.

**Power Generation, Storage and Distribution - State of the Art, Potential Solutions, and Technology Gaps**

The Power Technology Panel was moderated by Lee Mason from the Space Technology Mission Directorate at NASA Headquarters and the panelists were Len Dudzinski from NASA Headquarters talking about radioisotope and fission power systems, Bob Sievers, Director of Advanced Energy and Power at Teledyne Energy Systems, talking about fuel cells and radioisotope thermoelectric generators, Erik Brandon from the NASA Jet Propulsion Laboratory talking about advanced batteries, and Paul Alburtus from the Department of Energy Advanced Research Projects Agency talking about energy storage.

Power technology is a critical factor in surviving and operating through the lunar night for periods of up to 354 hours and temperatures of 100 K or less. If ample power were continuously available, it would enable uninterrupted system operations and also provide energy for supplemental heating. To provide substantial levels of power continuously, a fission reactor is a known technology that would meet that requirement. Other approaches involve generating and storing solar power when sunlight is available and using the stored energy during darkness. The fourteen Earth days of darkness and extreme cold experienced at most locations on the Moon presents what is probably the most demanding energy storage challenge that will be faced in the exploration of the solar system. This section will focus on power generation and storage while the next section will focus on the closely related subject of thermal management.

Power is an enabling technology for space missions and in particular for lunar surface operations. Power systems require early development and technologists should be given flexible requirements to maximize the range of potential system-level solutions. Some power system technologists have noted the critical need to make the International Space Station more accessible for power technology testing.

Batteries: There are a wide variety of battery chemistries and design architectures that can be selected to fit almost any mission's needs. Compared to other energy storage options batteries are most appropriate when the required power level is lower (less than 1 kilowatt). There are many cases where batteries can be used to supplement another primary power system or to power specific distributed elements of a surface system. Batteries generally require careful thermal management (with heaters for cold conditions and radiators and louvers for hot conditions) and the requirements on the battery system will depend on the overall design of the mission.

- In one type of mission there may be good thermal management already available with waste heat from avionics, solar insolation, an RTG, and/or a large primary power source to maintain battery temperatures within a modest range. Commercially available battery technology might be used in this case.
- Missions that, out of necessity, have a wider operating temperature range and lack robust thermal management systems will require batteries with advanced chemistry electrolytes to withstand more severe temperature ranges, other customized systems, or technology beyond the current state-of-the-art. Solid state battery technology would greatly increase low-temperature tolerance and reduce concerns about battery freezing.

Regenerative Fuel Cells: A regenerative fuel cell power system would use surplus solar power during the day to electrolyze water into hydrogen and oxygen reactants which are stored for later use by the fuel cell. At night the stored reactants are converted back into water in a process that generates electrical power. The resulting water is stored for future fuel cell cycles. The fuel cell reaction would also generate waste heat that can be useful to augment thermal management. The technology is well-developed however further adaptation for lunar surface conditions is required. A lunar surface system scaled for 10 kilowatts is estimated to require storage volume for 2000 kilograms of water. There is a potential to use residual lander propellants as fuel cell reactants as well as lunar derived hydrogen and oxygen or water. If lunar-derived water is considered for use in a regenerative fuel cell, the purity of the water will be an important factor.

Radioisotope Thermoelectric Generators: Radioisotope thermoelectric generators (RTG's) use thermocouples to convert the heat released by the decay of Plutonium 238 into electricity. RTG's have been used for 50 years on space missions including on the Apollo instrument packages, which operated through many lunar nights. This technology can clearly be useful in surviving and operating through lunar night as long as the power requirements are modest. The current Multi Mission RTG (MMRTG) can generate about 110 watts. Advanced RTG's are being studied with the goal of reaching power levels of 200 to 500 watts. The current supply of RTG's is limited by the availability of plutonium but plans are underway to re-establish production to support continued use of RTG's for future space missions. This work is a partnership between NASA and the Department of Energy.

NASA has been working with other agencies to improve the process for launch approval of RTG's and similar systems including the objective of increasing the opportunity for possible use of these systems on commercial missions.

Fission Reactors: Fission reactors have been considered for space applications since the early years of spaceflight and some reactors have been flown in Earth orbit. The current development effort is for the "Kilopower" system which is a sterling-based generator that can produce 1 kilowatt of electric power with a system mass of 400 kilograms. This design can be scaled up to 10 kilowatts with a system mass of 1500 kilograms. If development continues, this system could be flight ready by mid 2020's. The Kilopower concept is intended to support power needs for operations on the surface of the Moon or Mars. It might also be used on in-space platforms or vehicles. Since power requirements are often underestimated, the modularity of the Kilopower concept is an attractive feature.

The Kilopower concept is designed to use highly enriched uranium fuel. An analysis of highly enriched uranium (HEU) and low enriched uranium (LEU) fission reactors was conducted to examine how scaling impacts power production and overall mass. It was found that HEU reactors will always be lighter than LEU reactors for comparable energy outputs. However, at higher energy outputs the mass of the heat rejection and power conversion portions of the reactor grow for both types of reactors. Due to other potential advantages of employing LEU fuel aside from performance, LEU fueled reactors may be attractive option for space applications when the required power level is high. The "Pylon" is a commercial LEU fission reactor system concept that is predicted to be able to provide from 10 kilowatts to one megawatt electric power. This reactor is based upon the direct Brayton cycle and uses a noble gas as its medium.

ARPA-E: The Department of Energy's Advanced Research Projects Agency (ARPA-E) has a number of technology projects of potential relevance to lunar surface power. They are interested in

Long-duration electricity storage has taken on greater importance for terrestrial applications since wind and solar power have reached the tipping point where they are now the lowest cost source of energy. Since wind and solar power generation can be intermittent, storage capability is essential. Their energy storage duration goals are in the 10 to 100-hour range, while the lunar night last 350 hours, but the investments in storage technologies may benefit lunar systems in any case. Candidate technologies include flow batteries, mechanical systems, thermal systems, and chemical systems.

ARPA-E is also interested in high-energy batteries for terrestrial vehicles and aircraft. These technologies may also have crosscutting benefits for stationary and mobile systems on the lunar surface.

There is a new trend in nuclear generator development going toward smaller modular systems that can be factory-built. This approach may be relevant to the type of nuclear systems that are needed for lunar operations, where the reactor must be transported to its destination and placed in operation with a minimum of logistical support.

Other Power Concepts: There are other less conventional power concepts that might offer benefits for surviving and operating through the lunar night. Wireless power beaming could be used to deliver power from an orbiting satellite to a surface base or rovers when the surface location might otherwise be in darkness. Power beaming has the advantages of being easily scalable to meet increasing power needs and the ability to provide data links to lunar vehicles as well. Power beaming or reflection of solar light might be used locally from the rim of a permanently shadowed crater or in polar regions, from a sun-lit area to an area in darkness.

Novel concepts for energy storage include flywheel devices that store energy in a mechanical form or superconducting inductive loops that could take advantage of the natural vacuum and cryogenic temperature conditions in shadowed areas.

**Thermal Management Systems, Strategies, and Component Design Features - State of the Art, Potential Solutions, and Technology Gaps**

The Thermal Management Technology Panel was moderated by Rubik Sheth from the NASA Johnson Space Center and the panelists were Eric Sunada from the NASA Jet Propulsion Laboratory talking about robotic missions, Chad Bower from Paragon Space Development Corporation talking about commercial systems, and Kurt Sacksteder from the NASA Glenn Research Center talking about the thermal wadi concept.

Thermal Environment: Some important factors about the lunar environment that need to be considered in relation to thermal management on the Moon:

- The lunar surface generally has a very high thermal absorptivity.
- Any nearby hills will be a source of infrared heating for any surfaces facing them and hills and other features can interfere in efforts to radiate to space.
- There are differences in designing thermal management systems for polar regions compared to other latitudes. Near the poles, the sun angle will be very low and local topography can have a much greater impact on lighting and thermal radiation.
- Lunar dust is a good insulator and it will increase the thermal absorptivity of any surfaces that it covers. The presence of dust can be an advantage or disadvantage depending on the circumstances.
- Due to the vacuum conditions on the Moon, convection is not available as a means of transporting heat.
- Within pressurized volumes convection can be used for heat transfer but with $1/6^{th}$-gravity, the convective performance will be different from that on Earth.
- The vacuum conditions can be a benefit and a resource in thermal management.
- The challenges of very high temperatures during the lunar day and especially at lunar noon must not be overlooked in developing integrated thermal management system designs.

System Strategies: Some basic strategies for keeping systems warm during the lunar night are:

- De-couple elements from the cold environment by disconnecting from or disabling radiators. Thermal switches are one way to de-couple from radiators and there have been significant recent advancements in this technology.
- Provide insulation – make systems adaptable and reconfigurable to the extent possible with deployable, retractable devices. It should be noted that multi-layer

insulation (MLI) typically used as shielding from external solar heat is not as effective in retaining heat.

- Minimize the ratio of mass to exposed area in the design or make the system reconfigurable to adapt to cold conditions
- Provide heaters, with the understanding that this requires more power or adds other constraints. There are a variety of heating approaches:
    - Resistive heaters – these require power and mass
    - Radioisotope heater units (RHU's) - provide approximately 1 Watt of heat in a 40 gram package, there is a limited and regulated supply of RHU's and they are expensive (there are 43 in stock but plans to produce more)
    - Chemical heaters – provide 0.1 to 0.26 kW-hr/kg, mature technology
    - Reclaim waste heat from avionics and other components
    - Combustion heaters – provide approximately 1 kW-hr/kg - immature technology
- Move to a sheltered area that provide cover or warmth such as under a lander, garage, or a natural or adapted feature such as a pit, etc.
- Construct a shelter with regolith or material brought to Moon (see thermal wadi concept below)

Advancements in materials engineering over the past few decades may provide a range of new solutions for thermal management. One additional strategy is to use of low-temperature-tolerant electronics and other components to the greatest extent possible.

NASA JPL has developed an advanced high efficiency heat switch for cold environments that operates on a warm-on/cold-off basis. During the lunar night this heat switch would be able to cut-off the thermal path to the system radiator.

NASA JPL, under NASA STMD sponsorship, has also developed bulk metallic glass gears and a gear box for use in cryogenic environments. The gear box has been tested successfully tested at 75 K. This gearbox has the advantage of not requiring lubrication and can be constructed via an injection molding process.

<u>Thermal Wadi Concept:</u> One concept for creating an artificial heat source on the Moon is the "thermal wadi" concept. Normal lunar regolith has very high thermal insulation properties and will not provide a very good source of radiative heat during the lunar night (it has low thermal diffusivity). However, if the regolith is consolidated by melting, it's thermal diffusivity can be increased by two orders of magnitude, becoming a very good heat sink. In one approach to creating a thermal wadi, a solar concentrator would be used to heat and melt an area of the regolith surface creating a slab about 50 centimeters thick. Solar insolation will naturally heat this slab during the day. If radiative losses are blocked during the night, the slab can provide heat to a rover or other element located above it. The slab would start at a temperature of about 100 C during the day and remaining above 0 C during the night. A 50-centimeter thick block, after exposure to the sun through the lunar day, can provide 25 watts(thermal) for the duration of a lunar night.

Sintering of regolith could provide some degree of increased thermal diffusivity and consolidation of regolith might be accomplished in other ways but melting of the regolith is necessary to obtain the greatest effect.

Rovers could be designed to take advantage of nighttime thermal wadi heating with special surfaces on the bottom of the rover. However, the design would need to account for undesired heating effects from the surface during the day. If a network of thermal wadis were created across a portion of the lunar surface, rovers could move from one to another during the day, stopping at night to absorb heat.

The thermal wadi concept has been studied since at least 2012 and some subscale testing has been done. However, larger scale demonstrations have not yet been done and would be needed to validate the concept.

If a consolidated regolith slab is established in a permanently shadowed area where it can radiate to space, a cold sink can be created. An additional variation of the thermal wadi concept is a novel approach to power generation created by exposing one regolith slab to daily solar heating and another nearby slab set up in a permanently shadowed area. If the two slabs are connected with a heat engine, electrical power might be generated.

## The Economic Business Case for Creating Lunar Infrastructure Services and Lunar Markets

The theme for the Commercial Panel was "understanding the economic business case for creating lunar infrastructure services and lunar markets". The moderator was Allison Zuniga from the NASA Ames Research Center Space Portal. The panelists included George Sowers of Colorado School of Mines, Dennis Wingo of SkyCorp Inc., Dennis Poulos of Poulos Air and Space, Mohamed Ragab of iSpace, and Rolf Erdmann of PTScientists.

The discussion on an economic business case for commercial lunar development focused on power as a utility service since power is a key element of surviving and operating through the lunar night. It was noted that we tend to underestimate the amount of power that will be needed for any operations beyond basic scientific investigations. It was recommended that NASA establish realistic power requirement goals to help define the most suitable power architectures for various levels of activity and to identify any gaps requiring technology development. It was also noted that NASA could benefit commercial development by establish standards for interfaces related to power and communications.

A panelist noted that if we want to encourage commercial power providers on the Moon, NASA or other users need to establish a price point at which they will purchase power on the Moon. The existence of that price point is essential to enable private investment. One commercial estimate was that power might be offered economically on the surface of the Moon at a rate of $100 to $150 per kilowatt-hour. This compares favorably (considering the relative remoteness) to the rate that US military forces have paid for electrical power in Afghanistan, which was claimed to be as much as $30 per kilowatt-hour.

A major inhibitor to commercial investment and development of power or other services is the lack of a well-defined and stable customer base or market. It was stated that commercial providers will not become engaged in lunar development if the lunar enterprise is limited to only science objectives. But if there is a sustained human presence and resource utilization, there will be a sufficient market for power, not only locally but globally. With respect to the science focus, it was noted that NASA efforts have been driven by the science and exploration goals under the guidance of decadal surveys and other long-range plans. There is no comparable decadal plan for commercial development and having one would be helpful.

While the discussion mainly focused on power as a commercially-provided service it was also noted that there is a contrasting model in which the government is the provider of infrastructure and private industry is the user. There appeared to be a split among those in the discussion with some saying that the government should be the customer for commercially-provided electrical power, propellant, and communications services and others who said the government should be the utility-provider so that commercial ventures can concentrate on other activities.

Historically, the US government has provided significant infrastructure with examples being the transcontinental railroad, interstate highway system, seaports, and airports. But it may be that the government role, with some exceptions, should be limited to the pioneering phase with private operators introduced rapidly, as has been the case with satellite communication. The proper roles of the public and private sector are probably case-specific and may depend upon the scale of the infrastructure element and the risks involved in its deployment and operation, the range and stability of the customer base, the capital investment needed, and the feasible profit margin. While commercial services were discussed very generically, there may be distinct differences among providing a true operational service, providing a facility, or selling a commodity such as electricity or fuel.

Public-private partnerships were discussed as a way to mitigate some of the difficulties in getting commercial enterprises started on the Moon. There was, however, a caution given, that typically both private and public partners often begin negotiations on public-private partnerships with unrealistic expectations, each believing the other party will be providing the majority of the investment. Actual, successful public-private partnerships normally require relatively equal contributions.

Compared to market stability and level of confidence needed to enable large scale investment, technology readiness was not described as a major concern. Given adequate transportation capabilities, it was stated that existing system solutions such as solar panels with batteries as storage could be established on a scale to support power levels of many kilowatts. For higher power levels, fission reactors would likely be needed.

Power beaming, while more novel, was described as a technology that would be easier to implement on the Moon, with no atmosphere, than at Earth. Using solar power as a primary source, power beaming from lunar orbit could be accomplished at almost any scale, with the advantage of being able to direct the power to multiple, dispersed sites, if needed. Power beaming might be an elegant technical solution to surviving the lunar night. Power beaming could be used locally, such as from a crater rim to a rover within the crater. Power beaming systems might also incorporate communications channels as part of their operation.

It was pointed out that there will be a challenge in selecting one or a few specific locations to establish major infrastructure to support power generation on a large scale, with any of the fixed power generation systems such as solar or fission. To enable more global lunar operations and the dispersed sensor networks desired for some of the key science objectives probably requires modularity and portability. Another alternative for global power may be power beaming from orbit.

Although not strictly part of the issue of surviving and operating through the night, much of the discussion related to propellant production as a commercial operation. That is, mining lunar ice and producing oxygen and hydrogen rocket propellants as a service. As with power, the key to encouraging development of commercial propellant providers is establishing a dependable market and stable price for the propellant. The relevance of this subject to surviving the lunar night comes from the fact that propellant production not only offers a very large potential return on investment in terms of space transportation costs but brings with it, out of necessity, power generation on a scale that would likely enable other activities on the Moon to be able to operate throughout the day/night cycle.

**International Space University Summer Project "Lunar Night Survival"**

At the International Space University Summer Session in 2018, a team of students conducted a design study on "Lunar Night Survival". The study was sponsored by NASA and the European Space Agency. It was a multi-disciplinary study covering the technical, legal, political, and financial aspects of a lunar development. A summary of the study was provided by study team members, Ilaria Cinelli and Matt Henderson.

Future lunar exploration will involve a combination of human and robotic elements engaging in a variety of activities: science and exploration, resource prospecting, space tourism, and preparing for future exploration of other planetary bodies. In an era of renewed interest in lunar exploration, spacefaring nations are evaluating missions that enable a sustained human presence on the Moon, commencing within the next decade. Reliable, scalable power generation and distribution systems will be the keystone in supporting such missions, especially those that require operation during lunar nights, in which the absence of direct sunlight and the extreme temperature variations create an exceptionally inhospitable environment. In these periods of darkness, temperatures may drop several hundred degrees Celsius within minutes of sunset, and subsequent electrostatic changes of the lunar regolith present additional complications.

The primary feature of the design solution, the Power Cell, is able to withstand these challenges and enables survival of lunar nights. It is based on space-proven power systems, such as photovoltaics, fuel cells, batteries, and the newly demonstrated Kilopower fission technology. Kilopower is a compact fission reactor that can produce up to 10 kW of power for over ten years. Together these systems can provide reliable power for several astronauts.

To support the power solution, a legal and economic framework was formulated to enable future power-related activities in space under a regulatory and financial body called the International Space Power Organization (ISPO). Within ISPO, an Outer Space Energy Regulatory Authority would assume regulatory responsibility to ensure compliance with the relevant treaties and international law, while the Outer Space Energy Development Bank will facilitate economic development. These agencies would cooperate to facilitate activity on the lunar surface by both private and public actors.

The complete project report and other information are available at this weblink:
https://www.lunarnightsurvival.com

**Open Discussion Summary**

The concluding open discussion was moderated by the Workshop Chairs, Andrew Petro from the Space Technology Mission Directorate at NASA Headquarters and Renee Weber from the NASA Marshall Space Flight Center.

A tiered approach was discussed in which science missions are characterized as 1) orbiters, 2) small payloads to the surface that do not require night survival, 3) larger payloads that require survival, 4) rovers that require survival, and 5) sample return. Only tiers 3 and 4 necessarily require night survival although sample return missions might be enhanced by longer duration operations. In this characterization, science can make progress at each tier and the important thing is to get started. Another related observation is that while it might be practical for a rover to simple survive the night by hibernating, most scientific networks need to operate continuously. Fortunately, the power requirements for distributed network stations may be relatively low.

While much of the workshop discussion centered on either surviving the night in the sense of hibernation or maintaining full operations throughout the day/night cycle it was mentioned that there is an intermediate state in which the systems are designed to operate at a predetermined lower level. This more adaptive approach might be a very practical compromise in which individual payloads or multiple surface assets collectively optimize their constrained power budget.

In the discussions, modularization and standardization were frequently mentioned. From a commercial perspective, standards help lower the cost of doing business and establishing standards was generally viewed as a government role. Beyond the commercial perspective, modularization and standardization can also lower the barriers-to-entry and enable more diverse participation, as has been seen with the rapid and widespread growth of cubesats. When participation in an enterprise becomes broader and more diverse greater innovation generally results.

The International Lunar Network (ILN) was discussed as a worthy endeavor to once again pursue. The ILN would benefit from continuous operations and so might be an early demonstration of these capabilities with a distributed global network. International cooperation may be especially helpful in network operations, such as communication.

The newly established Commercial Lunar Payload Services (CLPS) program prompted substantial discussion and raised questions about how payloads might be supported in terms of the thermal management and power services that commercial landers might provide to payloads. It is expected that the early commercial lunar landers will be very limited in these services and there may be opportunities for secondary services to enable payloads to survive and operate through the night. An important aspect of the CLPS program is that it represents a significant change in NASA’s acceptance of risk. NASA is accepting greater risk for the lander missions and payload providers must also accept this greater risk as well.

One line of the discussion was based on the question: Why are we going to the Moon? Apollo-style lunar missions could be conducted only during lunar day using well-established approaches and technologies. If the purpose is limited scientific exploration, those types of mission would benefit greatly from night survival and minimal operations at night but moderate advancements in thermal management system design are probably sufficient. However, if the purpose is a sustained presence including substantial scientific exploration and commercial development then surviving and operating through the night become essential requirements. If the underlying reason for government support of a sustained presence on the Moon is an economic one, then there needs to be a reasonable expectation that the efforts will result in growing a new business sector and that implies permanent infrastructure on the Moon to provide an anchor tenant to spur investment. Developing the capabilities needed for lunar night survival and operations will also help enable future operations in other thermally-extreme space environments, thus increasing our ability to explore and operate sustainably throughout the solar system.

## APPENDIX A: Workshop Organizing Committee and Participants

**Organizing Committee**

Andrew Petro (NASA Headquarters), Samuel Lawrence (NASA Johnson Space Center and LEAG), Greg Schmidt (Solar System Exploration Virtual Institute), Renee Weber (NASA George C. Marshall Space Flight Center), Sarah Noble (NASA Headquarters), Benjamin Bussey (NASA Headquarters), Bradley Bailey (Solar System Exploration Virtual Institute), Gregory Chavers (NASA Marshall Space Flight Center), Alison Zuniga (NASA Ames Research Center), David Korsmeyer (NASA Ames Research Center)

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**APPENDIX B: Poster Session Participants**

Titles are hyperlinks to online abstracts

| Authors | Title and Summary |
| --- | --- |
| Evans M. E., Ignatiev A. | *Lunar Superconducting Magnetic Energy Storage (LSMES)* [#7001]<br>This study seeks a method to efficiently store electrical energy without using chemical batteries, by applying terrestrial technology based on a superconducting coil and a persistent magnetic field located in a lunar permanently shadowed crater. |
| Nandini K., Usha K., Srinivasan M. S., Pramod M., Satyanarayana P., Sankaran M. | *Passive Survivability of 18650 Lithium-Ion Cells Through Lunar Night Environment Scenario* [#7002]<br>Present study describes passive survivability of commercially-off-the-shelf 18650 lithium-ion cells tested in an environmental scenario similar to onset and progress of lunar night that is at cryogenic temperatures under vacuum for 336 earth hours. |
| Poulos D. D. | *Data Encoded Laser Wireless Power (DELWP) for Lunar Polar Applications* [#7003]<br>Data encoded high power fiber lasers illuminating specialized tuned photovoltaic panels designed for power transfer will provide reliable, continuous power and data during periods of limited solar illumination, including into the dark polar craters. |
| Van Cleve J. E., Weinberg J. D., Neal C. R., Elphic R. C., Weed K., Mills G., Dissly R. | *Darkness Visible: Instrumentation and Thermal Design to Access the Hidden Moon* [#7005]<br>We show mission concepts for a long-lived geophysical network and in-situ investigation of volatiles in the lunar polar cold traps, and Ball instrument and thermal technology enabling survival, situational awareness, and operations in the dark Moon. |
| Herring J. S., Mackwell S., Pestak C. | *Small Modular Fission Reactors that Enable Affordable and Sustainable Lunar Enterprise* [#7006]<br>We will present the results of a study looking at the use of a LEU-based Small Modular Fission Reactor (SMFR) in the 40 to 100 kW range for lunar activities, building on the results of NASA's HEU-based Kilopower project. |

Colaprete A., Elphic R. C., Shirley M., Siegler M.

*Multi-Lunar Day Polar Missions with a Solar-Only Rover* [#7007]
The lunar poles offer opportunities for solar-only rovers to survive and operate many lunar days. Presented here are examples of rover traverses that take advantage of the unique polar illumination environments to operate across multiple lunar days.

Eppler D. B., Budden N. A.

*Lighting Constraints to Lunar Surface Operations* [#7008]
An investigation into lunar surface ambient lighting levels indicates that, for most nearside locations, illumination will be adequate throughout a large portion of the lunar night to conduct surface activities.

Bugby D. C., Clark P. E., Hofmann D. C.

*High Performance Thermal Switch for Lunar Night Survival* [#7009]
A high performance differential thermal expansion (DTE) thermal switch was developed to enable solar/battery powered lunar surface science payloads. The measured thermal switch performance is: 5 W/K ON, 0.002 W/K OFF, and 2500:1 ON/OFF ratio.

Nunes D. C., Carpenter K., Haynes M., de la Croix J. P.

*Shifting the Paradigm of Coping with Nyx on the Moon — a Ground-Penetrating Radar Case* [#7012]
A multi-static, autonomous ground-penetrating radar instrument, MARGE, will incorporate strategies to be more tolerant of the lunar diurnal thermal cycle.

Wani S. C., Shah U. B., Kothandhapani A., Garg P., Sahai M., Garg M., Nair S.

*Requirement Analysis and Night Survival Concept for Z-01 Landing Mission Using Fuel Cell* [#7014]
Only three missions have survived the lunar night, using Radioisotope Thermo-Electric Generators and Radioisotope Heating Units. This paper discusses the challenges to survive lunar night and presents a fuel cell-based concept as an alternative.

Plata D. S.

*Lunar Roads: Strategies for Remaining in the Sunlight* [#7017]
By driving westward on the slowly rotating Moon, telerobots could remain in the sunlight while compressing the regolith in order to make basic, reduce-dust roads.

Powell T. M., Siegler M. A., Molaro J. L., Paige D. A.

*Leveraging In-Situ Regolith Properties for Nighttime Heating* [#7018]
Despite large temperature fluctuations at the lunar surface, thermally coupling to warm nighttime materials (rocks, subsurface, etc.) present in-situ might provide some heating and reduce the engineering payload necessary for surviving the night.

Dillon R. P., Borgonia J-P. C., Roberts S. N., Hofmann D. C., Kennett A., Firdosy S. A., Wilcox B. H., Hales S., Smith J. D., Schuler J., McEnerney B., Shapiro A. A.

*Bulk Metallic Glass Gears for Lunar Night Capable Actuators* [#7019]
BMG Gears is developing unheated, cold-capable gearboxes for use in cryogenic environments such as lunar night. The enabling alloy properties, cryogenic test performance, part processing, qualification, TRL, and infusion challenges are discussed.

Carroll K. A.

*Lunar Surface Gravimetry Surveying Through the Lunar Night* [#7020]
Lunar surface gravimetry is a powerful technique for probing the Moon's subsurface structure, using a gravimeter on a static lunar lander or on a lunar rover. Measurements spanning multiple lunar days will increase accuracy and resolution.

Guven U. G., Singh A. K. S.

*Utilization of Nuclear Power for Moon Missions: Nuclear Power Generation Using Helium Cooled Reactor for Moon Habitats* [#7021]
Abstract discusses using helium cooled nuclear reactors in Moon habitats to supply continuous power to the habitat as well as any future processing/manufacturing plants on the Moon.

Nieczkoski S., Dreyer C. B., Blair B., Rostami J.

*Material Selection for Mechanical Mechanism Survival and Use in the Lunar Night* [#7023]
Survival of spacecraft mechanisms is challenging due to low polar temperatures. Structural and cutting materials enabling drilling and mining under deep cryogenic conditions are currently being tested under the NASA Early Stage Innovation program.

Guzik M. C., Gilligan R. P., Smith P. J., Jakupca I. J.

*Regenerative Fuel Cell-Based Energy Storage Systems for Lunar Surface Exploration* [#7024]
The data presented in this paper provides a method to determine the critical parameter values of a Regenerative Fuel Cell (RFC) system in order to perform high-level mission architecture trades, with a focus on surviving the lunar night.

Williams J.-P., Greenhagen B. T., Paige D. A.

*Seasonal Temperature Variations in the Polar Regions of the Moon* [#7026]
Mapping of temperatures in the south polar region with LRO's Diviner Lunar Radiometer Experiment shows how temperatures within 5 degrees of the pole vary considerably with season.

Eubanks T. M.

*Milliwatt Lunar VLBI Beacons: Surviving the Lunar Night* [#7027]
Milliwatt radio beacons could establish a lunar VLBI network for science and navigation in cislunar space, ideally operating for decades. Small, gm-scale Americium-241 batteries are proposed to meet the power and longevity needs of these networks.

Fuqua Haviland H., Poppe A. R., Fatemi S., Delory G.

*The Importance of Nightside Magnetometer Observations for Electromagnetic Sounding of the Moon* [#7010]
Nightside Time Domain Electromagnetic Sounding has the capability to advance the state of knowledge of the field of lunar science. This requires magnetometer operations to withstand the harsh conditions of the lunar night.

Ignatiev A.

*The Use of Lunar Resources for Energy Generation on the Moon* [#7013]
The resources of the Moon can be used to develop an electrical energy system for the Moon. This can be accomplished by leveraging vacuum deposition technology and lunar resources to fabricate a low-cost and scalable lunar power grid.

Baiden G. R., Blair B. R.

*Adapting Terrestrial Technology to the Design of a Night-Survivable 10 Meter Lunar Polar Prospecting Drill* [#7016]
This paper will explore the possibility of a 10 meter cryogenic lunar polar drill that could 'survive the night' and that would enable the collection of scientific data that could validate current models for polar resources.

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| Vaughan R. | *Mission Design and Implementation Considerations for Lunar Night Survival* [#7029]<br>We present some of the design, development, cost, and schedule impacts of dealing with problematic night time lunar conditions, whether for near-equatorial or near-polar landed lunar missions. |
| Farmer J. F., Alvarez-Hernandez A., Breeding S. P. ,Lowery J. E. | *Advanced Thermal Techniques and Systems Design Enable Long Duration, Continuous Day/Night Operation of Robotic Science Landers and Payloads on the Lunar Surface* [#7030]<br>Recent developments in NASA and commercial space capabilities and plans support and call for increased exploration of the lunar surface. Lunar exploration objectives vary widely from geophysical research to human exploration and resource prospecting. |
| Clark P. E., Bugby D. C., Hofmann D. C. | *Low-Cost Distributed Lunar Surface Networks Enabled by High Performance Thermal Components* [#7031]<br>Credible opportunities for delivery of small payloads to the lunar surface via commercial landers are emerging in the coming decade. |
| Cataldo R. L., Mason L. S. | *Lunar Night Survivability Achieved by Radioisotope and Fission Power System Technology* [#7032]<br>Options for advanced RPS and Kilopower systems will be discussed and compared to alternate power system solutions. |
| Morrison C. G. ,Deason W., Eades M. J., Judd S., Patel V., Reed M., Venneri P. | *The Pylon: Near-Term Commercial LEU Nuclear Fission Power for Lunar Applications* [#7033]<br>Nuclear energy provides not only the ability to survive the 354-hour lunar night, but the ability to thrive. |
| Hecht M. H., Lubin P. | *Satellite Beamed Power for Lunar Surface Assets* [#7034]<br>The confluence of several factors now make beamed power systems practical for solar system exploration in the near-term. This is particularly true for lunar exploration. |
| Barnhard G. | *Challenges of Space Power Beaming: Mission Enabling Technology for Continuous Lunar Operations* [#7035]<br>This presentation will outline opportunities to leverage and extend the Xtraordinary Innovative Space Partnerships, Inc. (XISP-Inc) Technology Development, Demonstration, and Deployment (TD3) mission for Space-to-Space Power Beaming (SSPB). |