TECHNICAL BRIEF

Lunar Surface Power System for an Extreme Environment

The National Aeronautics and Space Administration (NASA)[1], which is an independent agency of the U.S. federal government responsible for the civil space program, aeronautics research, and space research, is developing a Lunar Surface Power System (LSPS) in the extreme environments of the moon as part of the Artemis Missions[2]. CenterPoint Energy[3] has been supporting the effort and has engaged EPRI. The LSPS plans to include various power sources and loads connected by a distribution system. EPRI performed two types of analysis for the developing LSPS. The first is on Standards for the electric system components and the other on how best to assess the electric system Reliability.

The extreme environment of the moon will make the construction and operation of the LSPS challenging. The Moon temperatures ranges from -180°C at night to +120°C during the daytime. A Lunar day is approximately 27.3 Earth days, with periods of darkness near the equator of over 300 hours. In the South Pole region, locations have sunlight for much of the lunar day. Other lunar conditions that need to be considered in the design include lunar dust, known as regolith, as well as a vacuum environment, and space radiation. Regolith is a dusty material that has a fine particle structure, is abrasive, and susceptible to becoming electrostatically charged.

EPRI evaluated known distribution system, electrical component Standards to determine their applicability to the lunar extreme environment. These Standards address components that are designed and manufactured for terrestrial environments. It was determined that there is no existing guidance on how electric system components would need to be designed for use in a lunar environment.

EPRI also assessed the LSPS Reliability using a Probabilistic Risk Assessment (PRA) model to comprehend the risks and inform the challenges in both the design phase and during operation of the LSPS. A PRA provides the tools to assess the impact of the lunar extreme environment on the LSPS to verify that the LSPS meets the reliability targets.

STANDARDS

To facilitate lunar exploration, research, and resource utilization, electric distribution infrastructure will be required and needs to be designed to Standards for the environment. However, typical distribution system components are designed for use in a terrestrial environment; the extreme operating conditions of the lunar environment were not considered in Earth-based component designs.

1 https://www.nasa.gov/
2 https://www.nasa.gov/humans-in-space/artemis/#:~:text=With%20NASA’s%20Artemis%20campaign%2C%20we,term%20presence%20on%20the%20Moon
3 https://www.centerpointenergy.com/en-us/pages/selfid.aspx

The objective of this research was to review existing electrical distribution infrastructure component standards, assess their applicability to the lunar environment, and identify the gaps that must be overcome to enable standards development for power distribution system components deployed on the lunar surface.

Review of Standards Applicability

EPRI reviewed standards from several organizations, including those specifically developed for electric distribution as well as applicable standards developed for other industries, such as mining and petrochemical. In summary, several organizations develop and maintain such standards, including IEEE, IEC, ANSI, and NEMA. However, they have been developed in the context of terrestrial operation. Standards used in nuclear power, such as IEEE 323 and IEEE 383 provide some guidance. Lunar design conditions include a vacuum environment, solar radiation, no moisture, a lot of regolith, and extreme temperatures that can rapidly change. Hence, the LSPS will likely have fundamental differences from that found on Earth. For example, bare electric conductors could potentially be directly buried in the electrically insulative regolith to provide radiation shielding for the conductors while isolating them from lunar technicians and machinery.

Gaps Identified

The review of existing medium-voltage equipment and component standards revealed a large gap between the requirements for terrestrial applications versus those in a lunar service environment. For example, designs for service on Earth include bulky shielding and weather-resistance materials selection that would not apply on the moon. Also, some of the environmental stressors on the moon are not applicable on Earth. For some components, such as the cable and related connectors, the design requirements may become simplified such as vacuum interrupter-based switches that can be adopted from terrestrial designs. And transformer designs and materials require significant research and development time. Elimination of transformers with an all-direct current system design would remove that complexity.

In general, the technical gaps between Earth-based electrical components and equipment are large and, in some cases, significant to the point where new development and testing programs would likely be required.

Next Steps

There are no current standards that cover the related equipment and component requirements. For the Artemis program, the driver for standards will need to be directed by NASA and/or its contractors. First steps would likely include bringing together a group of stakeholders to determine the functional requirements and potential design tests for the components identified.

RELIABILITY

There will be challenges in assessing the reliability, resiliency, and maintainability of the LSPS components. A probabilistic risk assessment (PRA) model can be used to inform these challenges in both the design phase and during operation of the LSPS. Sensitivity studies and importance measures from a PRA can be used to make decisions about redundancy, diversity, or equipment protection during the design stage. During the operational stage, it can be used to inform the maintenance and spare parts strategies, as well as identify when risk management actions may be required to control the risk due to the current configuration of the LSPS.

This research:

- Provides insights on how a PRA model can be used to address these issues.
- Provides a methodology for building a reliability assessment program.
- Includes considerations of data sources that could be used to estimate the reliability of LSPS components.
- Defines risk importance measures that could be used to make risk-informed decisions.

- Considers the extreme environment of the moon.
- Details the benefits of using a risk monitor to assess real-time risk during LSPS operation.
- Provides a summary of the milestones expected to be part of the LSPS design and operation and how the PRA could be used at each milestone.

The recommended approach to assess the risk and reliability for the LSPS is to use PRA with the development of event trees and fault trees to model the LSPS systems. The ASME/ANS PRA standards provide requirements for commercial nuclear power plants, but many of the requirements can be generally applicable to the LSPS. Existing PRA tools are available to support the development of a PRA model for the LSPS.

Implementation of a Reliability Assessment Program that uses PRA risk insights throughout the design phase will allow for risk-informed design decisions. This results in a well-designed LSPS that will meet all of the required risk targets.

Recommendations

Recommendations for how a PRA could be used to support the LSPS are:

1. Create a PRA model for the LSPS to use in all phases of the LSPS' lifecycle; conceptual design through operations.
2. Evaluate the ASME/ANS PRA standards for existing nuclear plants and advanced reactor designs.
3. Define the risk metrics to be used when analyzing the LSPS to set risk targets.
4. Establish a Reliability Assessment Program for the LSPS that defines target reliability requirements and verifies the design meets the target values. Monitor the performance of the LSPS to ensure the implementation of the reliability targets in the design continues to be met in the operational system.
5. Group similar components for data collection and estimation of failure probabilities.
6. Set up a data tracking system that will record the number of demands and run hours for equipment and the number of failures of components based on the operation of the LSPS.
7. Continue Earth-based simulation of the LSPS hardware, even after the LSPS becomes operational to refine failure rates and gather information about repairs.
8. Evaluate any failure on the moon or on Earth-based simulations for the potential for a common-cause failure to generate estimates for common cause failure of components used in the LSPS.
9. Establish strict administrative controls over planned maintenance and testing to ensure cross-train activities are not permitted at the same time.
10. The LSPS should use a real-time risk monitor to assess the risk when the configuration changes.

END NOTES

The full Standards report titled: *Extreme Environment Power Systems Standards: Evaluation and Gap Analysis* is available for download by clicking on the title.

The full Reliability report titled: *Proposed Risk Management Methodology to Assess Reliability for a Lunar Surface Power System* is available for download, please click on the title.

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

THE MATERIAL IS BASED UPON WORK SUPPORTED BY NASA UNDER AWARD NO 80NSSC22M0300 AND CENTERPOINT ENERGY, INC.

EPRI PREPARED THIS REPORT.

EPRI CONTACTS

EVA GARDOW, *Program/Area Manager*
973.479.3776, evgardow@epri.com

JOE POTVIN, *Distribution Systems Program Leader*
413.445.3709, jpotvin@epri.com

JOHN WEGLIAN, *Technical Leader, Principal*
704.595.2763, jweglian@epri.com

ERIC THORNSBURY, *Technical Leader, Principal*
202.293.6347, ethornsbury@epri.com

For more information, contact:

EPRI Customer Assistance Center
800.313.3774 • askepri@epri.com

3002030348 **May 2024**

EPRI

3420 Hillview Avenue, Palo Alto, California 94304-1338 USA • 650.855.2121 • www.epri.com