2024 TECHNICAL UPDATE

Extreme Environment Power Systems Standards

Evaluation and Gap Analysis

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ABSTRACT

Establishing standards for power distribution system components is fundamental to system reliability and safety. Standards generally apply to operation of components within well-defined function requirements and environments. While some component standards include provisions for abnormal operation or use in abnormal environments, there is little guidance in the existing standards for components that experience continual use in “extreme environments.”

This report reviews the applicability of existing standards for component use in extreme environments. The material is presented in the context of the recognized extremes of the lunar environment.

Keywords

Distribution system
Equipment standards
Lunar environment

EXECUTIVE SUMMARY

Deliverable Number: 3002029273

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Product Title: Extreme Environment Power Systems Standards: Evaluation and Gap Analysis

Primary Audience: Stakeholders involved in developing distribution systems component standards for application in a lunar environment.

Secondary Audience: Anyone considering distribution components standards for extreme environments.

KEY RESEARCH QUESTION

Efforts are underway to establish a permanent lunar research stations that would include various power sources and loads connected by a primary distribution system. However, existing distribution systems use components designed and manufactured for terrestrial environments. There is no existing guidance on how these components would need to be designed for use in a lunar environment.

RESEARCH OVERVIEW

EPRI conducted an extensive review of existing distribution component standards in the context of suitability for application in a lunar environment. The research also identified gaps in the standards that would need to be addressed to establish distribution system component standards for the lunar environment.

KEY FINDINGS

- Several organizations develop and maintain distribution system component standards, including IEEE, IEC, ANSI, and NEMA.
- All distribution system component standards have been developed in the context of terrestrial operation. There is no provision for operation in an environment as extreme as the lunar environment.
- Standards such as IEEE 323 and IEEE 383 provide more generalized guidance, directing that components need to be qualified for use in their operational environments and for the stressors they may experience.
- The design of lunar surface distribution system components will be based on conditions not found on Earth, including a vacuum environment, no moisture, and extreme temperatures that can rapidly change. Hence, the lunar distribution system 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.

- Development of lunar distribution component standards will require several types of stakeholders with expertise in distribution components and expertise in the lunar environment.

WHY THIS MATTERS

This research highlighted the gaps between terrestrial distribution system component standards and future lunar distribution system component standards. This shows that existing standards cannot be applied with small modifications for the lunar environment. Ultimately, this investigation showed that new standards are needed.

HOW TO APPLY RESULTS

This research provided background on the drivers behind standards and how they differ in terrestrial and lunar environments. This report provides the fundamental material required to start developing standards for the future lunar distribution system. Prior to standards development, stakeholders should review the material contained within.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- This document would be of interest to any standards organization working on developing new standards for extreme environments, particularly the lunar environment.

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1 PROJECT OVERVIEW

The NASA Artemis program has a wide range of goals that ultimately lead to long-term habitation, wide-ranging exploration, and development of industrial-scale mining and materials production capability to support missions beyond the moon, including Mars. The latter includes hydrolytic conversion of lunar polar ice to produce hydrogen and oxygen. To support this multi-tiered mission, the requirement for significant electrical power is a major focus from the outset. Significant planning will go into power production, siting of the initial commercial facilities, the optimum location for climate considerations, and a focus on the local mineral and geological resources. Key modules for habitation, power production, mining, and hydrolytic conversion of ice are well along in development and the mission will begin with human flights in 2024, followed by siting the Habitation and Logistics Outpost (HALO). To interconnect the modules to follow, a lunar analog of a terrestrial power grid will be essential. The lunar environment in the selected south pole location is very harsh by comparison with terrestrial environments and imposes an unprecedented set of operating challenges on the components of the future power grid.

Establishing standards for power distribution system components is fundamental to system reliability and safety. Standards generally apply to operation of components within well-defined function requirements and environments. While some component standards include provisions for abnormal operation or use in abnormal environments, there is little guidance in the existing standards for components that experience continual use in “extreme environments”.

This report reviews the applicability of existing standards for component use in extreme environments. The material is presented in the context of the recognized extremes of the lunar environment. The structure of this report includes:

Section 1 – Project Overview

This section presents proposed functional parameters for a lunar surface power system. This section also discusses the operating environment found on the moon, as documented in prior NASA studies and missions.

Section 2 – Materials Descriptions

A brief review of the materials discussed in subsequent sections is provided to better familiarize readers with materials use and challenges of their application, particularly on the lunar surface.

Section 3 – Electrical Standards Drivers, Development, and Governance

This section describes why standards are created. This section also presents examples of how standards are developed and maintained.

Section 4 – Review of Standards Applicability

Most standards were developed for application in well-defined terrestrial environments. This section reviews those standards and the conditions for which they are applicable.

Section 5 – Discussion of Gaps

This section reviews existing standards in the context of the lunar environment, illustrating where new power system component standards are needed.

Section 6 – Next Steps to Create Lunar Surface Power System Component Standards

This section consolidates the core content from the previous sections to build a potential roadmap for establishing a standards body for lunar surface power system components.

Section 7 – Potential Alternate Approaches for Medium-Voltage Distribution *Infrastructure*

Finally, this section provides preliminary subject matter expert insights and considerations for designing a lunar surface power system. Medium voltages normally include voltages ranging from 1 kV up to 46 kV.

Lunar Surface Power System Description

Planning and technology development are underway to establish a permanent base camp on the lunar surface. To support that effort, sustainable power sources and infrastructure is required. The expected loads include [1]:

- In-Situ Resource Utilization (ISRU) (60+ kW) – ISRU includes the mining, collection, transportation, and processing of lunar materials, such as ice. Due to the high energy requirements, these operations would be restricted to periods of heavy insolation.
- Habitat (20 – 50 kW) – The current expectation is that a crew of four will remain in the base camp for 30+ days during periods of heavy insolation. Four of these missions are expected to take place annually.
- Lunar Science/Exploration (500 W per rover, power beaming requirements) – To support scientific exploration of the lunar environment, researchers will require transportation. Power beaming may also be needed to power scientific instruments or other loads.

To support these loads and have reserve capacity for additional loads and future growth, the planned power system will be designed for 1 MW. The loads and sources are expected to be established as independent microgrids that are interconnected by a medium-voltage primary distribution system. The microgrids are expected to include [1]:

- Habitation a few kilometers from the Shackleton Crater
- ISRU Production near the rim of the Shackleton Crater
- ISRU Excavation at the base of the Shackleton Crater

Each microgrid is planned to be up to 6 km away from its nearest neighbor, requiring the distribution system to include multiple current-carrying conductor runs that are multiple kilometers long. Beyond microgrid connections, the primary distribution system will also need to include provision for connecting planned power sources, such as a fission reactor, and additional future loads. Figure 1 presents one general potential DC electrical system layout. An AC distribution system would be similar but would also require components to convert DC to AC power, i.e., inverters and rectifiers. The system must also make provision for repairs.

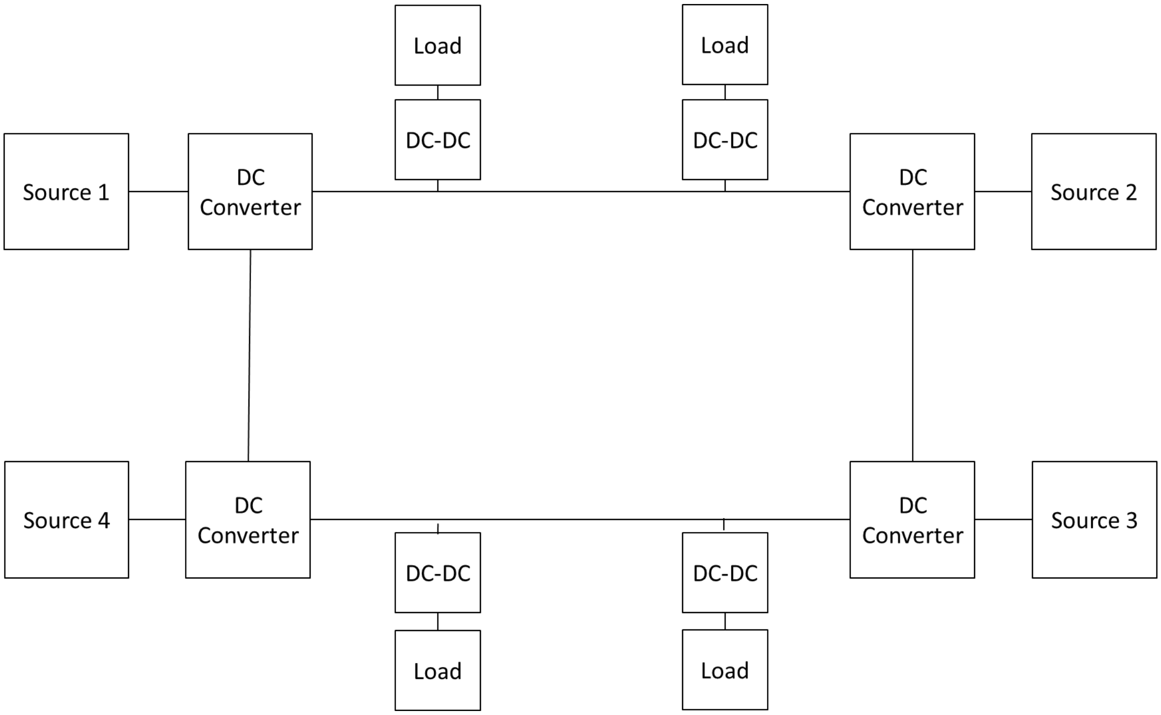

Figure 1. Example DC electrical system, including sources, loads, and voltage converters

Distribution System Components

Fundamentally, the purpose of an electrical distribution system is to distribute generated electrical power to the connected loads. Multiple generating sources are expected, and loads may be added progressively. Distribution systems require multiple components to function, including:

- Conductor/cable – The electrical ‘conduit’ used to transport power from source to load.
- Connectors – Components used to connect conductors electrically and mechanically to electrical equipment and to one another.
- Switches – Devices used to isolate line segments or interrupt load. These may be manually operated or equipped with automation.
- Voltage Converters – To facilitate efficient transport of energy over long distances, higher voltage levels are used, usually exceeding 1 kV. Typical loads require lower voltages, so the voltage needs reducing prior to end use. DC systems employ DC-DC converters, e.g., buck-boost type converters. AC voltage conversion is typically accomplished through use of AC transformers constructed with a magnetically coupled core and windings.

- Electrical Protection – In the event of voltage or current transients that could damage equipment connected to the distribution system or the distribution system itself, precautions are essential. Surge arresters help prevent overvoltages. Current limiting through switches electronically configured for automatic restoration by isolating a defective generating source or load.

- System Monitoring and Diagnostics – Modern distribution systems have increasingly high reliability expectations so more distribution system owners are deploying monitoring systems and sensors to provide real time information on equipment condition and system health. However, there are currently no standards guiding the design of this equipment. The Institute of Electrical and Electronics Engineers (IEEE) is currently developing a guide to provide test protocols for medium-voltage smart grid sensors.

Engineers select distribution system components and their ratings based on system requirements and abnormal operating conditions that could arise. While vendors usually have distribution components certified as passing specific design tests, other factors such as historical experience with similar materials, products, or vendors often influence purchasing decisions, as standards only provide minimum performance criteria that vendors may choose to simply meet or elect to surpass.

Lunar Surface Environment

A distribution system designed for operation on the lunar surface would face operating conditions not experienced in a terrestrial environment. These conditions include:

- *Thin atmosphere* – The atmospheric pressure on the lunar surface is 3×10^{-15} bar, 14 orders of magnitude less than the earth's atmospheric pressure at sea level [2]. While this eliminates moisture, a common contributor to terrestrial material degradation, this also leaves the surface unprotected from radiation.

- *Temperature extremes* – Lunar temperatures fluctuate based on exposure to sunlight. Regions that experience periods of extended insolation reach a high temperature of 130°C and a low temperature of -173°C. Permanently shadowed regions, such as the base of the Shackleton Crater, can experience temperatures as low as -250°C. This wide temperature range can produce high mechanical stresses as materials expand and contract unless appropriate design measures are undertaken.

- *Long lunar days and nights* – The length of one full lunar day is approximately 28 Earth days; at the lunar equator, there are 14 Earth days of insolation and 14 Earth days of darkness. At the lunar poles, periods of insulation last much longer. The Shackleton crater experiences approximately 20 Earth days of sunlight and 8 Earth days in darkness. Along with the extreme temperature changes, the distribution system will need to continue operating to transport energy from reserves to the lunar system loads.

- *Low Gravity* – The lunar surface has approximately 1/6th the gravitational force experienced at Earth sea level. This could impact work practices and installation approaches.

- *Radiation* – The lunar surface is exposed to more intense and a wider range of radiation types than experienced on the earth's surface. Examples include intense ultraviolet light emissions, in addition to gamma and neutron radiation. These have damaging effects on many materials used on earth, including electrical components. Semiconductors may experience significant degradation due to heavy ion flux experienced on the lunar service.

- *Regolith* – The lunar surface is composed of a material termed 'regolith'. This dusty material has fine particle structure, it is abrasive, and susceptible to becoming electrostatically charged. While electrically insulating, it could potentially degrade and wear electrical contacts and other electromechanical equipment.

- *Micrometeorites and other Cosmic Debris* – Without a significant protective atmosphere, cosmic particles and the debris from solar system body collisions exposes the lunar surface to high energy particle impingement.

Section Summary

To facilitate lunar exploration, research, and resource utilization, electric distribution infrastructure will be required. 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 these component designs.

The following sections of this report address existing component standards, their applicability to the lunar environment, and reviews the technical challenges that must be overcome to construct a viable power distribution system on the lunar surface.

2 MATERIALS DESCRIPTIONS

A broad range of materials find applications in the electric power industry; however, the materials used for power distribution narrows that range significantly based on considerations of fundamental performance, cost, formability, established history, and other technical and practical considerations, including the limitations imposed by established industry standards.

This section reviews the basic materials used in manufacturing distribution system components. A fundamental background in these materials will help the reader better understand the applicability and limitations of these materials for the lunar environment.

Conductive Metals

The only two electrically conductive metals that are encompassed in the present power industry standards include aluminum and copper. These metals differ significantly in weight / density (8.96 g/cm^3 for copper versus 2.7 g/cm^3 for aluminum) and electrical resistance (resistivity of aluminum is 52% higher than copper). Carrying current produces heating based on these properties and this heat must ultimately be dissipated into the environment. Copper can be in the form of bare metal, or with a tinned or plated surface. Metals are immune to most of the lunar surface stressors, such as UV radiation and thermal extremes. Direct long-term impingement by gamma radiation will lead to grain boundary attack and embrittlement. Direct exposure to neutrons will lead to microscopic surface pitting and cumulative erosion. Protective measures might include direct burial of selected components, such as cable and connectors, while other components can be protected by shrouding. High energy impacts by micrometeorites can also be prevented by shrouding.

Ceramics

Ceramics appear in few modern medium voltage equipment applications. Ceramics appear in the form of housings for vacuum interrupters, as electrical bushings, insulators for supporting bare conductors, and occasionally as components of arc-breaking systems in load-break switchgear. Ceramics are essentially geological materials and are thus long-lived, however heavy on a unit basis and can be brittle. Ceramics for medium voltage electrical applications are based on alumina. Medium voltage equipment/component standards do not define the type of ceramic materials for any particular application. Ceramics are immune to the effects of UV radiation and most forms of ionizing and non-ionizing radiation. While thermal extremes will not affect ceramics, these are sensitive to high rates of temperature change. Ceramics can be formulated, and component mechanical designs can be combined to appropriately select ceramic components.

Polymers

Polymers for medium voltage electrical applications find primary use as insulating, jacketing, and shielding for medium voltage cables and cable accessories, such as splice housings, separable connection bushings, and multi-way connections. The electrical insulation materials covered in the standards for cables include crosslinked polyethylene (XLPE), ethylene-propylene rubber (EPR), ethylene-propylene diene monomer rubber (EPDM), ethylene alkene monomer (EAM), and thermoplastic polypropylene (TPP). With the exception of XLPE and TPP, none are applicable as pure materials. While these contain a very low concentration of organic functional ingredients, such as an antioxidants and cross-linking byproducts, these are otherwise pure. Reference documents in the public domain address the properties of these materials. The other insulation systems include large concentrations of inorganic materials, such as kaolinite, zinc oxide, iron oxide, lead oxide, titanium dioxide, and others that may exceed the concentration of the base polymer on a unit weight basis. These also contain various organic materials, all of which are combined in proprietary formulations for which specific performance information is unavailable.

Polymers for cable and cable accessory shielding applications include ethylene vinyl acetate (EVA), ethylene ethyl acrylate (EEA), primarily. These contain a high concentration of carbon black, on the order of 35 - 45% by weight to render them semiconducting. While the pure base polymers have documented properties, the sensitivity of the compounded shielding material has only been established for normal cable operating conditions plus elevated temperature aging. Similar polymers or EPDM rendered semiconducting by addition of a high concentration of carbon black may be used for cable accessory housings.

Polymers for cable jacketing applications cover a wide range of materials, none of which are used in pure form. Cable jackets are applied primarily for physical protection of the cable core during installation, though it may also serve a moisture barrier and/or flame-retarding role.

The medium voltage cable and component standards do not stipulate the base polymer, nor the formulation of polymeric compounds used for any category. Instead, these are qualified for the application by the component manufacturer or by the compound supplier. The single common factor with respect to the electrically-stressed medium voltage equipment polymers is that all are a form of hydrocarbons.

Polymers are sensitive to the effects of ionizing radiation of all types. Damage by gamma radiation and UV, for example, causes polymer chains to split. This chain scission process creates reactive chain ends that may spontaneously form new chemical bonds through the process termed ‘crosslinking.’ Though this process can render a polymer more durable in the short term, the gradual effects are catastrophic. The ever-shorter polymer chains produced result in a volume loss and accumulation of high internal tensile stresses. Spontaneous fractures will result and may cause complete failure. Most polymers used for established terrestrial electrical applications have a maximum long-term service temperature limit of 130°C. While polymers are available with higher thermal limits, their applications for electrical components have been limited by cost and forming complexity, for example. Shrouding can be used to prevent exposure to ionizing radiation, however protection against thermal extremes will involve reduction of polymer use and selection and development of more robust materials and designs.

Additional thermal concerns with polymers arise where there are bonded interfaces, such as between the insulation and shield of a typical medium voltage cable. The shear generated by differences between thermal expansion coefficients would lead to interfacial fractures and subsequent electrical failures. Further, most of the common polymers for electrical applications become brittle at -40°C. This would render impossible the uncoiling of cables from a reel.

Section Summary

The polymeric materials in common use for medium voltage electrical applications are not specifically controlled in the corresponding industry standards. All the polymers are organic materials that may or may not contain a high concentration of inorganic materials. The weak link with respect to operating these materials in harsh lunar environments focuses on the base hydrocarbon polymer. Temperatures at the low end of the lunar environment and at the upper end are well beyond what the conventional electrical insulating and protective materials can survive. Metals and ceramic materials are more robust due to their higher bonding energy and density. It is expected that the development of new materials will be necessary to facilitate long-term stability in a lunar environment. More discussion of this point is provided in Section 7.

3 ELECTRICAL STANDARDS DRIVERS, DEVELOPMENT, AND GOVERNANCE

Each distribution system component has one or more associated standards that provide design and application guidance. Standards often have many contributors from manufacturers, service providers, researchers, and utilities. In general, these groups have some experience with the relevant component from the design, testing, or user perspective. Component standards are intended to serve the end-user, but often require input from manufacturers, relevant industry groups, academics, as well as the end-user. Developing these standards often requires years, and they require periodic review and updating as design and materials evolve and the industry gains experience with the component.

This section review standards creation, including the drivers behind standards content, how standards are written, reviewed, adopted, and maintained.

Drivers

The broad objective of distribution system components has been to provide component end-users with a product that serves its function reliably and safely over a reasonable lifetime. More specifically, these can be addressed within the context of the operating environment and the challenges it presents. Significant differences are recognized between the terrestrial and lunar environments.

Terrestrial Environment

- Water – Moisture contributes to corrosion, polymer damage, electrical tracking, and other forms of degradation. Moisture also builds surface films on components that may lead to external tracking or flashover damage. Many standards include test requirements that expose components to combined moisture and electrical stress to better understand performance.
- Weather – Distribution systems must operate under a variety of conditions such as temperature extremes, rain, wind, snow, and flooding. Most component standards require testing to one degree or another of a component's ability to address these conditions, whether it be functional testing at elevated or low temperatures or exposing components to electrical transients simulating lightning surges.
- Wildlife – Field experience has shown that wildlife can cause equipment failure through contact with energized components, nesting on or near energized components, chewing on insulation, abrasive contact, etc.
- Workability – Work practices on earth for handling medium voltage equipment are based on physical forces that can be exerted by the average worker. Simple matters such as obtaining a ladder from a truck or an additional tool are familiar. Additional hardware can be obtained from a utility company work center or local supplier. Ergonomics also play a

role in some component designs. Standards may include requirements regarding anchoring locations or addition of lifting brackets to enable handling of heavy components. There are some unusual terrestrial environments, e.g., subsea and steep inclines, that are better suited for robotic installation and manipulation of components.

- Limited design constraints – Terrestrial equipment designs generally must meet standards and expectations from the utility company. Such considerations include size, appearance, weight of overhead equipment, and other considerations, however designs that exceed some of these expectations are not precluded.
- Interoperability – To better avoid interoperability issues between components, some standards have established common requirements for certain components. For example, IEEE 386 [3] provides dimensional requirements for loadbreak elbows, this is expected to allow an elbow from one manufacturer to connect with a bushing produced by another manufacturer.
- Cost constrained designs – On Earth, the cost of components and equipment are major considerations that may, in fact, compromise or limit some of the design features and materials choices that might otherwise result in longer-lived components.
- Manufacturer and user consensus – Standards affect component design and material selection. However, onerous standards requirements could lead vendors having to use exotic materials or manufacturing processes that would make products difficult to produce and/or unreasonably expensive. Hence, manufacturers and end-users provide input into standards in an attempt to balance expected reliability and safety with cost and adequate supply. These factors are largely experienced-based.
- Relatively accessible infrastructure – While not directly addressed in standards, the implicit philosophy behind most component designs is that they are relatively easy to access and maneuver around. Similarly, standards are being created to address issues such as limiting mylar balloon contact with overhead lines, a consequence of easily accessible infrastructure [4].

Lunar Environment

Development of most terrestrial standards for distribution systems have included implicit conditions such as operation in air or under water, temperature extremes that are limited by those observed on earth, and that the consequences of outages, while inconvenient, are often not a matter of survival. These conditions are not representative of lunar environments; the thin atmosphere can be approximated as non-existent, temperature extremes are greater than those experienced on Earth, and consequences of a power outage could be dire, necessitating redundancies, back-up systems, and components designed with inherently high reliability.

- Vacuum environment – Operating in a vacuum environment affects the ability to work on equipment, the ability of components to dissipate heat, and the behavior of electrical arcing and discharge events. Standards developed in a lunar environment will need to address challenges such as these as well as how to conduct representative testing. On the other hand, the absence of atmosphere eliminates key environmental issues. For example, there is no moisture available to contribute toward premature component degradation, one potential advantage of a lunar surface power system.

- Thermal extremes – Temperature extremes on the lunar surface are greater than those experienced on earth, ranging from -173°C to 130°C, and as low as -250°C in permanently shadowed areas. The materials, components, and equipment used on the moon will require testing over a wider range of temperatures.
- Ultraviolet (UV) radiation – UV radiation causes polymer degradation in a terrestrial environment but is much more intense on the lunar surface. Components used on the moon will need inherently high resistance to UV-induced degradation or have a protective barrier applied.
- Gamma radiation – Due to the earth's atmosphere, gamma radiation is not a concern for terrestrial distribution system components, except for those used in a nuclear environment. Because the lunar surface experiences gamma radiation exposure, lunar power system components will require appropriate testing to ensure acceptable performance.
- Challenging work environment – While some terrestrial operations require wearing special suits, particularly when there is a high arc flash potential, most do not. However, working on a lunar power system would require a suit equipped with a life-support system or specialized robotics. Therefore, power system components would either need to be designed to interface with robots, or components would need to be easily manipulable by lunar technicians.
- Low gravity – Having lower gravity than the earth's surface, setting and moving equipment on the lunar surface would be comparatively easier as a result of the reduced weight.
- Mission-critical reliability – While medium-voltage cables are electrically tested prior to shipping, many discrete components manufactured for terrestrial use are generally subjected to quality assurance protocols by testing a small number of components that represent the population. This is due to cost limitations and acceptance by the end-user that occasionally defective equipment may be found from time to time. However, defective equipment in a lunar environment could have more severe consequences. Components used in a lunar environment would likely require more stringent quality assurance testing to achieve the level of reliability required to maintain life support systems in living quarters and mission-critical activities, for example.
- Logistical constraints – Components will not be readily available on the lunar surface, hence there will need to be provisions for extra components retained in storage, potentially for extended periods of time. Component storage may be required outdoors if limited space is available in the established pressurized habitats on the lunar surface.

- User-directed – Rather than standards being created through consensus between vendors and end-users to optimize cost and function, the high reliability requirements and specialized environment would emphasize reliable, safe operation more than cost. Standards would likely begin as a set of requirements and specifications provided by the end-user, i.e., the lunar distribution system operator, and may evolve into a consensus standard as the industry matures.
- Acceleration and zero gravity environment tolerance – For now, lunar power system components will need to be manufactured on earth and transported to the moon. During transport, the power system components will be subjected to forces caused by high acceleration rates, approximately 3 G's. and vibrations of varying amplitude and frequency.
- Requirement for remote operation – While there are relatively frequent missions planned for the Artemis research station, there will be large amounts of time when the base will be unmanned. Even when there are lunar technicians present, they may not have the correct expertise to operate, repair, maintain, or manipulate the distribution system. Remote operation will need to be considered in terms of operating the lunar distribution system and any robots that could work on the system infrastructure.

Standards Development

International technical standards support the implementation and evolution of new technologies. Standards set out to establish a framework, usually based on requirements, for acknowledged best practices and minimum performance. The goal is to provide a clear and consistent platform for new or expanded use cases.

These standards are usually developed on a voluntary basis with the goals of

- Transparency – all of the activities and steps are undertaken on a schedule with published notices so that participants can contribute
- Openness and Impartiality – there are meaningful opportunities for all parties with an interest to make technically-based contributions that are then peer reviewed
- Consensus – generally consensus is achieved on technical topics, this is aided by requirements for the disclosure of affiliations
- Effectiveness – the documents use well founded technological developments to ensure to maximize the usefulness

In the context of the development of a lunar power system, it is worth reflecting that usually a proven / operational technical concept available from multiple vendors is in place before embarking on an international specification. Thus, the basic parameters (AC vs DC, voltage levels, power requirements, etc.) are known in the industry with a body of fundamental background work available to the participants within the specification groups. This is not the case for lunar power systems.

The three major specification development groups relevant to lunar power distribution are:

- CIGRE (Conseil International des Grands Réseaux Electriques)
- IEC (International Electrotechnical Commission)
- IEEE (Institute of Electrical and Electronic Engineers)

All three of these groups develop documents that are used internationally to support the development and implementation of standards. The processes used are slightly different between the organizations. The major components of the process are detailed in Table 1.

Table 1. Basic structure of international specification development for the three major bodies

	CIGRE	IEC	IEEE
Membership Basis	National		Individual or Entity
Scope	- Developed by a Task Force - Approved by a Study Committee and Technical Committee	Working Group formation decided by Technical Committee	- Developed by Chair and Vice Chair - Approved by Sponsor Body and New Standards Committee (NesCom)
Technical Work Responsibility	- Working Group led by a Convenor - Composed of one technical expert nominated by each National Committee	- Typically uses technical work from CIGRE - Project work conducted by representatives of National Standards bodies (One Country one Vote)	- Working Group led by a Chair and Vice Chair - Composed of individual members who participate consistently
			- Working Group led by a Chair and Vice Chair - Composed of individual entity members
Approval	- Consensus within the Working Group members - Consensus within the Study Committee National members	- Public Review - Final Draft International Standard (FDIS) Ballot	- Working Group Ballot - Sponsor Body approval - Public Review - Ballot of interested IEEE Standards Association Members (min 75% approval, 75% participation) - NesCom Approval
Revision	As required	5 years	≤ 10 years
Deliverables	- Technical Brochure – often treated as a specification prior to IEC adoption - Review Article published in ELECTRA - Presentation material	Technical Specification	

Section Summary

The need to develop a power distribution system for operation in the lunar environment is unprecedented. There are no current standards that would cover the related equipment and component requirements. For the Artemis program, the driver for standards will have to come from NASA and/or its contractors since there is no other need for such a power system. The standards would grow from the initial developments and experience gained through early development of such a system. There are a number of international standards organizations that might be suitable for establishing lunar power system standards, however, IEEE may be the best fit due to where it is based, primarily through one of the working groups.

4 REVIEW OF STANDARDS APPLICABILITY

The electric utility industry has contributed toward the development of distribution system component standards for decades, establishing minimum requirements to better ensure component reliability and safety. Distribution system components for extraterrestrial application should also be designed and tested to ensure operability in extraterrestrial environments.

Prior to developing brand new distribution component standards, NASA requested that EPRI review existing component standards to determine if existing standards could be tailored or partially adopted for the lunar service environment. This section presents existing distribution standards and provides their operational scope, including function and operating environment.

Note that most distribution components are controlled by standards created by multiple organizations. Each standards organization may also have multiple standards that address different classes of the component, e.g., voltage class, and for different applications, e.g., nuclear vs underground distribution medium voltage cables. Hence, this generates many documents with content that may be mutually exclusive or entirely duplicative. While many standards were reviewed in detail, those that were most common and those that address abnormal operating environment conditions are considered herein.

Distribution System Components

As discussed in Section 1, distribution systems typically include:

- Conductor and cable
- Connectors
- Switches
- Voltage conversion devices, such as AC transformers and DC voltage converters
- Electrical protection, such as surge arresters, fuses, and relays

Much of this equipment, excluding medium-voltage DC devices, has well-defined standards that guide design and ensure a minimum level of performance. Components not reviewed herein include:

- Civil infrastructure – This includes electric poles and foundations for overhead distribution and vaults, conduit, ducts, and transformer and switchgear pads for underground distribution.
- Grounding systems – Having high resistance, regolith inhibits good grounding. Ground resistance guidance provided by the National Electric Safety Code [5] suggests 25 Ω or less. This value is likely not attainable in regolith, suggesting that deployment of a dedicated system-wide shared ground conductor will be essential.

Conductor and Cable

This forms the backbone of the electrical grid and will carry all loads between the generating, storage, and end-use locations. Terrestrial cable designs are insulated with traditional olefinic or rubbery materials and include internal shielding components and a grounded neutral conductor for radial and axial electric stress control and for limiting the distribution of fault damage. Terrestrial cables are typically protected with an overall extruded jacket, available in a wide range of materials and thicknesses, in crosslinked and thermoplastic form. Cables are the subject of many standards that cover the wide range of materials and corresponding designs. The principal existing cable standards and what they address has been summarized in Table 2. The list of operating parameters has been edited and extended to include considerations that are specific to potential lunar applications. The column at the extreme right has also been added to indicate key requirements of the lunar operating environment specific to the Artemis program.

Of specific note is IEEE Std. 383 [6]. While the other standards reviewed only pertain to a relatively narrow temperature range when compared with lunar operating conditions, IEEE Std. 383 has provision for demonstrating the ability of the cable accessory to (a) survive in its operating environment without being prescriptive about the environment, and (b) that the cable accessory survive design-basis events, discussed in more detail in Section 5.

Table 2. Conductor standards examples and scope

Operational and Environmental Parameters	ICEA S-94-649 [7]	IEEE Std. 1242 [8]	IEEE Std. 383 [6]	Lunar Environment
Description	Shielded Concentric Neutral, Extruded Only	Petrochemical Refining	Qualifying Electric Cables and Splices for Nuclear Facilities	NA
Conductor Materials	Copper, Aluminum	Copper, Tinned Copper, Aluminum	Not specified	NA
Insulation Materials	XLPE, TRXLPE, EPR, EAM	EPR, XLPE, Paper Oil	Not specified	NA
Shielding Materials	Not specified	EPR, Polyolefin, EVA, EEA	Not specified	NA
Protective Materials	LDPE, HDPE, CPE, XLPE, LSZH, TPE, PP, PVC	PVC, CPE, CSPE, LSZH (ozone resistant, non-tracking) Includes metal armoring and laminated jackets Lead sheathing	Not specified	NA
Atmosphere	Air Water	Air Water Petrochemical	Most severe operating conditions	None
Exposure to Ultraviolet Radiation	Yes	Yes		Yes, 1300-1400 W/m^2
Installation Method	Direct buried, conduit, riser, aerial, submerged	Plant accessible		TBD
Maximum Operating Temperatures (°C)	Normal 90, Emergency 130 Normal 105, Emergency 140	Normal 90, 105 for EPR only		130
Minimum Operating Temperatures (°C)	Not specified	Tests include -40 cold impact and -65 cold bend for arctic installations		-173 (Exposed), -250 (Shadowed)

Table 2 (continued). Conductor standards examples and scope

Operational and Environmental Parameters	**ICEA S-94-649** [7]	**IEEE Std. 1242** [8]	**IEEE Std. 383** [6]	**Lunar Environment**
Operating Voltage	5 through 46 kV AC (Implied) DC Not addressed	5-35 kV AC (Implied) Includes 173% insulation level DC Not addressed	Most severe operating conditions	TBD
Gamma Radiation Exposure	Not specified	Not specified		Yes
Cosmic Particle Exposure	Not specified	Not specified		Yes
Regolith Exposure	Not specified	Not specified		Yes
Impact Test	Not specified	Not specified		Yes
Rapid Temperature Excursions	Not specified	Not specified		Yes
Ballistic Resistance Test	Not specified	Not specified		Yes

Connectors

Connectors are essential components of the cable system, linking conductors, power sources, and loads. These are available in many forms with designs and materials that range from complex shielded constructions to others that are bolted, with separate overlying shielded housings. Connectors may be simple, non-shielded devices for joining bare conductors used for overhead medium voltage wires in terrestrial applications. The principal standards and what they address are summarized in Table 3, addressing permanent connectors, and Table 4, addressing separable connectors. Permanent connectors are intended for permanent installation, whereas separable connectors may be disconnected and reconnected. Separable connectors are frequently used in underground distribution systems to break and isolate loads. These are shielded, rubber insulated designs, intended only for application with shielded cables.

The list of categories has been edited and extended to include considerations that are specific to potential lunar applications. The column at the extreme right has also been added to indicate key requirements of the lunar operating environment specific to the Artemis program.

In general, connector standards address thermal and mechanical performance. Overhead connectors may be under high mechanical tension while carrying current. Under rated operating conditions, connector temperatures should not exceed the temperature of the connected conductor. IEEE Std. 383 addresses connectors as well as conductors, discussed earlier in this section, prescribing that demonstration of these components in representative working environments is required for qualification.

Table 3. Permanent connector standards examples and scope

Operational and Environmental Parameters	IEEE Std. 404 [9]	IEEE Std. 48 [10]	ANSI C119 [11]	IEEE Std. 383 [3]	Lunar
Description	Extruded and Laminated Shielded Cable Joints 2.5 kV to 500 kV	AC Cable Terminations Used on Shielded Cables Having Laminated Insulation Rated 2.5 to 765 kV or Extruded Insulation Rated 2.5 to 500 kV	Testing Methods and Equipment Common to the ANSI C119 Family of Standards	Qualifying Electric Cables and Splices for Nuclear Facilities	NA
Connector Materials	Copper, Aluminum	Copper, Aluminum	Copper, Aluminum	Not specified	NA
Atmosphere	Air, water	Air	Air	Most severe operating conditions	None
Exposure to Sunlight	Yes	Yes	Yes		Yes, 1300-1400 W/m^2
Direct Burial	Yes	No	Not specified		
Operating Temperatures	-30°C to 50°C	-40°C to 65°C	15°C and 35°C		-250°C up to 130°C
Maximum Water Submersion Depth	7 m	NA	Not specified		None
Operating Voltage	69 to 500 kV	2.5 to 500 kV	Not specified		TBD
Rated Current	Equal to or greater than the cable it is designed for	Not specified	Not specified		TBD
Gamma Radiation Exposure	Not specified	Not specified	Not specified		Yes
Cosmic Particle Exposure	Not specified	Not specified	Not specified		Yes
Regolith Exposure	Not specified	Not specified	Not specified		Yes
Impact Test	Not specified	Not specified	Not specified		Yes
Rapid Temperature Excursions	Not specified	Not specified	Not specified		Yes
Ballistic Resistance Test	Not specified	Not specified	Not specified		Yes

Table 4. Separable connector standards examples and scope

Operational and Environmental Parameters	IEEE Std. 386 [12]	IEC 60502-4 [13]	Lunar
Description	Cable Accessory	Test requirements on accessories for cables with rated voltages from 6 kV (Um = 7,2 kV) up to 30 kV (Um = 36 kV)	NA
Atmosphere	Air	Air	None
Exposure to Sunlight	Yes	No	Yes, 1300-1400 W/m2
Direct Burial	Yes	Yes	TBD
Operating Temperatures (Able to Close and Separate)	-40°C to +65°C (-20°C to +65°C)	Not specified	-250°C up to 130°C
Altitude	1800 m (6000 ft)	Not specified	TBD
Maximum Water Submersion Depth	1.8 m (6 ft)	Not specified, addressed in different standard	None
Operating Voltage	2.5-kV to 35-kV, AC @ 49 Hz to 61 Hz (nominal)	6-kV to 30-kV	TBD
Rated Current	200 A, 600 A, 900 A	Dictated by operating temperature declared by the manufacturer	TBD
Additional Power System Constraints	Applies to grounded wye systems; for ungrounded wye or delta systems, select next higher voltage class product. Not recommended for ungrounded 35-kV systems		TBD
Gamma Radiation Exposure	Not specified	Not specified	Yes
Cosmic Particle Exposure	Not specified	Not specified	Yes
Regolith Exposure	Not specified	Not specified	Yes
Impact Test	Not specified	Not specified	Yes
Rapid Temperature Excursions	Not specified	Not specified	Yes
Ballistic Resistance Test	Not specified	Not specified	Yes

Switches

Switches are key components of distribution systems that enable loads and generating sources to be individually isolated for testing and troubleshooting. Switches have many designs including simple open-contact manually operated devices to others that include vacuum interrupters as the core switching component combined with electromechanical or manual operators. The principal standards and what they address has been summarized in Table 5. The list of operating parameters has been edited and extended to include considerations that are specific to potential lunar applications. The column at the extreme right has also been added to indicate key requirements of the lunar operating environment specific to the Artemis program.

In general, switch standards better ensure that the device exhibits an acceptable amount of heating when operating at rated current. Fault currents are also addressed. Switch contacts and hinged connections are prone to excessive heating if not designed correctly, leading to potential damage. Dielectric strength is usually verified, and some conditions, such as icing may be addressed. Some stressing of the switch may also take place prior to testing, such as opening and closing the mechanism to ensure it is well built.

Table 5. Switch standards examples and scope

Operational and Environmental Parameters	IEEE Std. C37.100.1 [14]	IEC 62271 – 102 [15]	Lunar
Description	IEEE Standard for Interrupter Switches for Alternating Current Rated Above 1000 V	High Voltage Switchgear and Control Gear: Alternating Current Disconnectors and Earthing Switches	TBD
Atmosphere	Air with some contamination	Air with some contamination	None
Exposure to Sunlight	Yes, 1044 W/m^2	Yes, 1000 W/m^2	Yes, 1300-1400 W/m^2
Wind Speed	Up to 40 m/s	Up to 34 m/s	None
Operating Temperatures (Able to Close and Separate)	-30°C to 40°C	-40°C to 40°C	-250°C up to 130°C
Altitude	Up to 1000 m	Up to 1000 m	NA
Humidity	Addressed	Addressed	None
Operating Voltage	Over 1 kV AC	Over 1 kV AC	TBD
Rated Current	Various	Various	TBD
Vibration	Addressed	Addressed	TBD
Icing Addressed	Yes	Yes	NA
Gamma Radiation Exposure	Not specified	Not specified	Yes
Cosmic Particle Exposure	Not specified	Not specified	Yes
Regolith Exposure	Not specified	Not specified	Yes
Impact Test	Not specified	Not specified	Yes
Rapid Temperature Excursions	Not specified	Not specified	Yes
Ballistic Resistance Test	Not specified	Not specified	Yes

Voltage Converters

The principal standards and what they address has been summarized in Table 6. DC-to-DC converters are beyond the scope of the present terrestrial medium voltage standards. Such converters may be used in traction and commercial power systems; however, the requirements for medium-voltage tolerance of solid-state voltage conversion devices renders these too expensive and bulky for the electric utility market. Medium-voltage AC conversion is accomplished through use of transformers. These are in widespread use for medium-voltage systems and addressed in numerous standards. The list of operating parameters has been edited and extended to include considerations that are specific to potential lunar applications. The column at the extreme right has also been added to indicate key requirements of the lunar operating environment specific to the Artemis program.

Table 6. Transformer standards examples and scope

Operational and Environmental Parameters	**IEEE Std. C57.12.00** [16]	**IEC 60076-1** [17]	**NEMA ST20** [18]	**Lunar**
Description	IEEE Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers	Power Transformers Part 1: General	Dry-Type Transformers for General Applications	TBD
Atmosphere	Air	Air	Air	None
Exposure to Sunlight	Addressed in C57.12.28	Not specified	Yes	Yes, 1300-1400 W/m2
Operating Temperatures	Up to 40°C	-25°C to 40°C	> 10 kVA, max 40°C (over 24 h period) < 10 kVA, max 25°C (over 24 h period)	-250°C up to 130°C
Altitude	1000 m	1000 m	1000 m (Max capability up to 4,500 m (15,000 ft)). See IEEE C57.96	NA
Operating Voltage	601 VAC and Higher @60 Hz	Not specified, power rating 1 kVA and greater	120 VAC - 1.2 kVAC	TBD
Rated Current	Sinusoidal	Sinusoidal	Sinusoidal	TBD
Vibration	Abnormal Condition	Not specified	Unusual Condition	TBD
Gamma Radiation Exposure	Not specified	Not specified	Not specified	Yes
Cosmic Particle Exposure	Not specified	Not specified	Not specified	Yes
Regolith Exposure	Not specified	Not specified	Not specified	Yes
Impact Test	Not specified	Not specified	Not specified	Yes
Rapid Temperature Excursions	Not specified	Not specified	Not specified	Yes
Ballistic Resistance Test	Not specified	Not specified	Not specified	Yes

Overvoltage Protection

Overvoltage protective devices have been designed to protect circuits from voltage spikes that can arise from switching surges, lightning strikes, and other events, only some of which may apply in the lunar environment. Solar storms and electrostatic discharges may be an issue on the moon. The protective devices protect components attached to the grid by limiting the maximum voltage to which they can be exposed. The principal standards and what they address has been summarized in Table 7. The list of operating parameters has been edited and extended to include considerations that are specific to potential lunar applications. The column at the extreme right has also been added to indicate key requirements of the lunar operating environment specific to the Artemis program. The corresponding IEEE and IEC standards set a thermal operating range from -40°C to 40°C and a maximum altitude of 1000 m. These limits relate to heat dissipation and are significantly exceeded by the lunar environment.

Table 7. Surge arrester standards examples and scope

Operational and Environmental Parameters	**IEEE Std. C62.22** [19]	**IEC 60099-4** [20]	Lunar
Description	IEEE Standard for Metal-Oxide Surge Arresters for AC Power Circuits (>1 kV)	Surge Arresters	TBD
Atmosphere	Not specified	Not specified	None
Exposure to Sunlight	Not specified	Not specified	Yes, 1300-1400 W/m2
Wind Speed	Not specified	Not specified	None
Operating Temperatures	-40°C to 40°C	-40°C to 40°C	-250°C up to 130°C
Altitude	Up to 1000 m	Up to 1000 m	NA
Humidity	Not specified	Not specified	None
Operating Voltage	Over 1 kV AC, 48 to 62 Hz	Over 1 kV	TBD
Rated Current	Various	Various	TBD
Vibration	Not specified	Not specified	TBD
Gamma Radiation Exposure	Not specified	Not specified	Yes
Cosmic Particle Exposure	Not specified	Not specified	Yes
Regolith Exposure	Not specified	Not specified	Yes
Impact Test	Not specified	Not specified	Yes
Rapid Temperature Excursions	Not specified	Not specified	Yes
Ballistic Resistance Test	Not specified	Not specified	Yes

Section Summary

The review of applicable medium voltage equipment and component standards reveals a large disconnect between the requirements for terrestrial applications versus a lunar service environment. Designs for service on earth include bulky shielding and weather-resistance provision and materials election that would not apply on the moon. Some of the environmental stressors that are intense on the moon are not applicable on earth, so there have been no efforts for related tolerance or protection. Thermal ratings for some components such as transformers and over-voltage protective devices are based on convective heat transfer to the surrounding air. Since this is all but completely absent on the moon, fundamental reconsideration of designs and qualification testing become paramount considerations. A relatively expedient adaptation of medium voltage devices used on earth is not possible to meet the profoundly different lunar conditions.

5 DISCUSSION OF GAPS

Section 4 summarizes the primary standards that apply to key components of the envisioned electric power distribution system. As noted in Section 4, there are a large number of significant gaps between what is covered in the present industry standards and what is needed for lunar environment service. Some of the most fundamental gaps are addressed in the following sections. As noted, some of these differences have multi-level impacts.

Temperature Extremes

The standards presented in Section 4 addressed temperatures as low as -65°C and as high as 65°C. Temperature extremes on the lunar surface are much greater than those experienced on Earth, ranging from -173°C (-280°F) to 130°C (266°F). This is a range of 303°C (546°F). In the permanently shadowed south pole area the temperature minimum is approximately -250°C (-418°F). The materials, components, and equipment used on the moon will require testing over a wider range of temperatures in addition to cyclic testing to replicate the 14 days of insolation and 14 days of darkness cycle and seasonal temperature fluctuations. The upper temperature range is not extreme for metals or ceramics and is only marginally extreme for most polymers. Thermoplastic materials in wide use for electrical applications have a melting temperature range with a lower limit of approximately 105°C (221°F) (i.e., polyethylene). Crosslinked polymers are qualified in the standards to a maximum continuous temperature of 130°C (266°F). The lowest temperature has no direct impact on the anticipated solid materials, with the single overarching concern with the rate of temperature change and any physical constraints that might apply a physical force to a rigidly frozen polymer, for example. Wherever dissimilar materials are joined, differences in thermal expansion coefficients will have to be modeled and full-scale designs tested to ensure reliable long-term service.

Section 7 of this report provides suggestion for novel design considerations for components and equipment needed for the lunar power grid. Most include approaches that have been simplified when compared to earth-based equivalents. This results in a reduced materials count and fewer interfaces that would be a concern with large thermal excursions.

Transformers represent an area of concern where significant development effort would be anticipated. In context of the Artemis project, transformers would be used for voltage conversion on the AC distribution system. The generation components will directly produce a DC voltage that would then have to be converted to AC through an electronic means, such as an inverter. The generating potential is envisioned to be on the order of hundreds of volts. However, transmission efficiency increases as voltage rises, as a rough guideline. A transformer would increase the voltage at the generating side to bring the grid potential to a medium voltage level. This might be on the order of 2 - 13 kV, based on terrestrial system design. This voltage would have to be reduced where the grid feeds many or most loads by use of another transformer. Direct grid voltage supply to large AC mining equipment motors may be possible. Despite these exceptions, other key elements, such as habitation and environmental control systems will require a significantly lower voltage. Since most, if not all of the loads identified in the Artemis plan are powered by DC, a voltage conversion from AC to DC would be essential again.

Typical transformers for terrestrial medium voltage AC applications are designed with a ferromagnetic core and coil immersed in mineral oil. The ratio of turns between the primary and secondary windings determines the step up/down ratio and the power rating depends on the wire gauge and heat dissipation. The windings are secured around a ferromagnetic core by use of wooden spacers in conventional earth-based designs. The windings are formed using enameled magnet wire. Insulating layers isolated the coil from the core. Leads to the primary and secondary windings enter the sealed transformer case through internal connections from the base of bushings. Typical transformers are fluid-immersed, using mineral oil, for example. This provides electrical insulation value while also carrying heat from the core to cooling panels on the outside of the tank. The suggested fluid may be semi-solid at the lowest lunar temperature, but it would be liquid and stable to the uppermost temperature. The suggested fluids have low vapor pressure so they would not be lost through gradual evaporation. Polyphenyl ether has the lowest vapor pressure of the proposed fluids.

Thermal extremes and excursions will require major re-thinking of transformer designs. To reduce the effects of thermal expansion, novel systems for coil supporting will be required and the coil insulation system technology may have to be changed to prevent cracking when a transformer is energized from a cold condition. Gas-insulated transformer designs are a mature technology, though these have limited heat dissipation performance. Transformers with solid polymeric insulation systems are also in production; however, these also feature limited heat dissipation performance and a large mass where different materials are bonded, thus creating avenues for significant thermally-induced stress accumulation.

Absence of Water

Terrestrial electrical components have been developed using materials and designs intended for protection against water exposure. This includes all forms of precipitation in addition to ground water exposure. Above-ground electrical components such as overvoltage protective devices, transformer bushings, and cable accessories are designed with insulated housings that include convoluted profiles. These profiles are designed to prevent water from forming continuous surface films over the device that might electrically bridge the path between an energized end and a grounded surface to which the device is secured. The shed also increases the creepage distance to reduce the impact of surface contamination. The creepage path is the length along the component surface between an energized and grounded point. On the lunar surface, regolith may accumulate on the surface of insulating material, acting like a contamination source. However, its impact on dielectric performance is unknown.

Absence of Atmosphere

The design of most medium voltage electrical components includes some level of essential heat transfer from the device to the surroundings through convection. This is imperative for transformers and less so for overvoltage protection devices. The earth atmosphere has a dielectric breakdown strength that is lower than that of a vacuum and is negatively impacted by moisture. The increased breakdown strength of the lunar vacuum environment reduces the spacing required between energized and grounded components, thus facilitating compact designs. Without any significant atmosphere, the effects of UV radiation and cosmic particle impact are greatly enhanced. Other forms of radiation are also more aggressive since there is no attenuating atmosphere.

Poor Electrical Grounding

The lunar regolith surface is dry, dusty. and has very low electrical conductivity. This contrasts significantly with earth-based soils where grounding is generally effective with simple driven ground rods. Grounding is critical for safety and essential for control of system overvoltages and fault energy dissipation, for example. In the absence of simple grounding options, a hard ground on the lunar surface may require boring with subsequent connection to a ground wire that is shared system wide.

Limited Maintenance and Repair Capability

The harsh lunar environment and the absence of a human presence pose challenges for troubleshooting, maintenance, and repair. Additional design requirements will likely be needed to enable robotic repair.

Design-Basis Events

The Artemis program will capitalize on what is known about the lunar service environment stressors, while also requiring planning for what can be reasonably anticipated. In addition to the expected stressors, electrical components and equipment might be subjected to impact while being handled by robots, for example. Meteorite impacts may result in impingement damage to components, hence ballistic resistance tests may be required of equipment. Cables may be dragged over the regolith surface while being deployed or buried.

Section Summary

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. For some components, such as the cable and related connectors, expedient options can be envisioned since these are actually simplified when compared to the same component designed for service on earth. Vacuum interrupter-based switches can be adopted from terrestrial designs without any fundamental reconsideration of the designs and materials.

Transformer designs and materials would require significant research and development time. Elimination of transformers with an all-direct current system design would remove that complexity.

6 NEXT STEPS TO CREATE LUNAR SURFACE POWER SYSTEM COMPONENT STANDARDS

Previous sections have addressed the key components of the envisioned Artemis medium-voltage primary distribution system with respect to existing related industry standards. The components used for terrestrial applications have fundamental limitations that preclude simple adaptation for use in the lunar environment. Further, many of the key design elements for terrestrial equipment are based on completely different operating conditions and factors such as precipitation, wildlife contact, public safety, and others. For terrestrial applications, there are comparatively few limitations imposed by component weight, labor requirements, maintenance needs and other practical considerations that are beyond the challenges imposed by the expense and logistics of a deployment site that averages 240,000 miles distant.

An overarching consideration for the lunar primary distribution system is whether it supports AC or DC power. This decision impacts selection of some of the distribution grid components, system complexity, reliability, and other major factors that include payload considerations, suitability for robotic installation/maintenance, and many others. A single-phase AC system would be more logical than a (terrestrial) three-phase system, considering that the generation is DC. Conversion from DC to AC simply for transmission efficiency introduces transformers into the generating a load ends of the power grid. These are poorly suited to the lunar environment and may be reason enough to design the system for DC only. Reliability will increase as the number of system components decreases. These considerations are not new, nor unprecedented in terms of prior review by NASA. The Lunagrid project has already dedicated resources to the design of fundamental generating system components but has not addressed the grid needed to construct the power distribution backbone. While it may appear to be a simple matter of interconnecting the generation and equipment loads via a cable, even the cable design would not be a simple adaptation of existing terrestrial technology that could be undertaken without significant research and testing.

Given these challenges, new standards are required to address distribution components used in a lunar environment. The standards would need to specifically address the lunar environment drivers described in Section 3. New standards would require contributions from a range of stakeholders, including:

- NASA representatives – NASA will need representation to ensure the objectives of the end-user are met and that mission integrity is preserved.
- Electrical engineers – Electrical engineers would help guide component specification in terms of power delivery requirements for the primary distribution and advise in terms of system ampacity needs and electrical protection requirements, for example.
- Material scientists – Components operating on the lunar surface will be exposed to a wider range of temperatures and a radically different operating environment than earth. The behavior of polymers, metals, and ceramics used to manufacture components and equipment will require careful attention.

- Lunar environment specialists – Material engineers will need to understand the working environment of the materials used on the lunar surface, and electrical engineers will need to understand how electrical transients could develop and impact the primary distribution system.
- Robotics Engineers – It is likely that components developed for lunar applications will need to have provision for robotic installation in the event that a lunar technician is unavailable, or conditions would impose an unacceptable risk for completing the work.
- Manufacturers – If components require at-scale production, manufacturers will need to provide input regarding the limitations of producing components on a large scale. However, manufacturer involvement may not be required in early standards development, other than providing their in-house electrical engineering and production expertise.

Given these stakeholders, the next steps to developing component standards for the lunar primary distribution system might include:

1. (Ideally) Developing one or more one-line diagrams showing the potential lunar distribution system power flow. This would illustrate the available power sources and load requirements as well as their locations, helping inform electrical insulation, equipment power ratings, and ampacity requirements.
2. Creating an engineering layout that describes the components needed for implementing the distribution system, whether based on AC or DC power.
3. Bringing together the group of stakeholders to determine the functional requirements and potential design tests for the components identified. Discussions would include:
    a. Review of the power system requirements (NASA)
    b. The distribution system design, including required components (electrical engineering)
    c. A review of the lunar environment and its stressors that would cause equipment degradation (lunar environment specialist)
    d. A review of material performance when exposed to lunar stressors (material scientists)
    e. Individual sessions for each component to identify appropriate performance requirements and design tests to ensure that the performance requirements can be met within the operating environment (all stakeholders)
    f. Drafting a standard outline and assigning authors for the content
    g. Defining a timeline for standard development, review, and parameters for accepting it
4. Designating a body for maintaining and reviewing the developed standards.

This is one approach that could be taken to develop the standard; however, it’s expected that some of the performance requirements may not achievable given current technology, and some research and development may be required.

In general, standard organizations may require years to develop standards. This is largely due to standards organizations being comprised of volunteers that have to fit standards activities into their already busy schedules. Standards body meetings usually only take place a few times per year. To meet current NASA deadlines, a more focused effort with a dedicated group of stakeholders is suggested along with well-defined deadlines.

7 POTENTIAL ALTERNATE APPROACHES FOR MEDIUM-VOLTAGE DISTRIBUTION INFRASTRUCTURE

Rather than attempting to adapt terrestrial electrical components and equipment for the lunar service environment, exploration of novel component design and materials considerations was undertaken. The concepts addressed below arose from a detailed review of the standards and considerations of the lunar operating environment that shares very little with the earth. These alternate concepts developed from a basic reconsideration of the design of key electrical components to eliminate design elements that are not necessary or suitable, while also focusing on enhancing simplicity to reduce risks and expedite development. These considerations are addressed on a component-by-component basis as follows. Note that implementation of any new technology in the lunar environment should be preceded by testing to ensure safe and reliable long-term performance.

Conductors

A complete departure from the terrestrial design of shielded and jacketed medium voltage cable is suggested, as addressed by the following key considerations:

- The conductor would be formed from aluminum to achieve the maximum balance between power capacity and unit weight.
- The conductor would be solid, with a rectangular cross-section to balance efficient on/off reel deployment and flexibility in the route direction.
- The conductor could be non-insulated due to high regolith resistivity and to eliminate concerns with insulation cracking under extreme cold conditions.
- A layer of polyether-ether ketone (PEEK) thermoplastic polymer could be applied to serve a dual insulation/protective jacketing role.
- An alternate insulation system might have the form of ceramic sleeves or beads that could be installed over the conductor; this option exists for terrestrial applications. However, the mechanical properties of ceramics, including their brittleness and potential for breakage under mechanical stress, should be carefully considered in the lunar environment.
- The conductors could be directly buried by continuous trenching to provide physical protection against equipment drive-overs, rockslide, and others. Terrestrial options include Horizontal Directional Drilling, using a vibratory plow, and application of open trenching devices.
- Vertical taps could be installed at planned intervals to facilitate connections to the buried conductors.
- A separate grounding conductor and spare primary conductors should be considered.

- To facilitate co-trenching and controlled isolation between parallel conductors, these could be separated at regular intervals by use of a pre-formed clamshell spacer that could be placed over the conductor, then held closed with a fastener.

Connectors

Shielded connectors will have no use in the lunar environment since they will not be placed on shielded cables. Bare or minimally insulated connectors could be developed with the following expedient considerations. Cast metal components should be avoided due to fracture propensity that would be enhanced by the extreme cold of the lunar surface.

Splice Type

- Splice connectors would be forged or deep-drawn aluminum with a solid body and pierced ends for conductor insertion and a solid insertion barrier at the mid-length.
- The connector would be closed around the 'line' conductor using shear bolts made captive to prevent loss.
- If the conductor is polymer-insulated, the internal surfaces of the connector would be serrated to penetrate through the insulation and establish rated-ampacity contact.

Tap Type

- Tap connectors would be hinged along the edge that connects over the 'line' connector, to ease installation and prevent dropping components, and closure would be executed with shear bolts.
- The tap connection would include additional shear bolts along two sides.
- If the conductors are polymer-insulated, the connectors would include some form of serrated internal surface to penetrate through the insulation to establish contact.

Overvoltage Protective Devices

Protective devices used for terrestrial applications represent a mature technology that is also used for protection of sensitive electronic circuits, though on a smaller scale. The radiation sensitivity of such components is recognized, however, shielding options are simple and direct.

- Zinc-based metal oxide varistor (MOV) technology would be used.
- Conductor attachment to the end of the MOV block would include constant spring force.
- The MOV device would be isolated from a metal radiation-hardened enclosure using ceramic supporting elements.
- The ground connection would be made to a system ground wire, as opposed to localized grounding to the high regolith resistance and to minimize circulating currents.

- The MOV would be equipped with a fuse or circuit breaker for isolating the device in the event of a short circuit failure.

Switches

- Switches would be based on vacuum interrupters to provide long-lived contacts, shielding from dust and cosmic particles, and maintenance-free reliability.
- Switch operation would be electromagnetic, with manual back-up to facilitate initial set-up, back up in the event of a control system or switch power interruption, as well as allowing automated operation.
- Switches operating electromechanically could be integrated with current transformers and a supervisory control system to provide overload protection and fault isolation. *As a significant benefit, this would eliminate the need for expendable fuses.*

Transformers

- Transformers will be insulated with a polydiphenyl siloxane fluid or polyphenyl ether and will be fitted with radiative cooling panels.
- Transformers will be mounted above-grade.
- Transformer tanks or enclosures will be painted with ceramic-based paint that limits solar heat absorption.
- Connections to the transformer with be made with bolted, non-insulated hardware.
- Considerations for novel lighter weight core materials should be investigated to reduce transport burden.

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