



Space Power Workshop
Celebrating 40 Years of Space Power: Supporting mission success in an increasingly agile space domain
April 25-27, 2023 | Torrance Marriott Redondo Beach | Torrance | CA

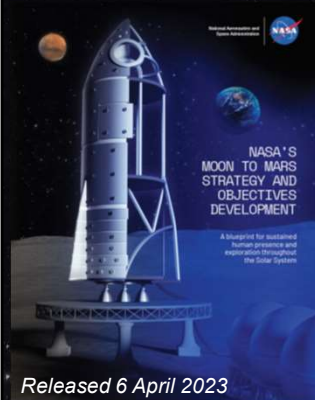
EXPLORESpace TECH
TECHNOLOGY DRIVES EXPLORATION

Lunar Surface Power Systems:

- Moon2Mars Objectives
- Agency Vision for Lunar Surface Power
- Power Building Blocks and Technology Gaps
- System Reliability and Resiliency

John H Scott | Principal Technologist, Power and Energy Storage, Space Technology Mission Directorate | April 9, 2023

NASA Moon2Mars Strategy and Objectives



Lunar Infrastructure (LI)

LI-1: Develop an incremental Lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.

Mars Infrastructure (MI)

MI-1: Develop Mars surface power sufficient for and initial human Mars exploration campaign

Activities depicted are not all funded or approved. This is a "notional future" developed to guide technology vision.

NASA Moon2Mars Strategy and Objectives



Omnibus Appropriation Bill – FY2023: NASA STMD

- **Lunar Surface Power.**—In addition to the reporting requirement in the House report, the agreement urges NASA to devote the resources required to ensure that lunar surface power systems, such as vertical solar arrays and fission surface power, are fully developed and prepared for deployment when the time for surface missions arrives in the mid-2020s. In lieu of the funding provided in the House report, the agreement provides up to \$40,000,000 for payload development and delivery to the lunar surface via the Commercial Lunar Payload Services (CLPS) program to execute a surface power demonstration by 2026. NASA is also encouraged to identify areas of alignment between nuclear propulsion and fission surface power research.
- **HOUSE LANGUAGE Lunar Surface Power.**—The Committee recognizes the need for steady, reliable, and uninterrupted power for future extended science and exploration missions on the lunar surface, particularly at the poles, and is supportive of past and ongoing investments in a mix of technologies, including both **Vertical Solar Array Technology (VSAT)** and **Fission Surface Power (FSP)**. The Committee notes the strategic benefits of a portfolio approach to lunar surface power, including affordability, mobility, and readiness. NASA is directed to sponsor the development and deployment of a mix of lunar surface power solutions in support of the Artemis program and **to enable the commercialization of lunar power as a service**. NASA is directed to report to the Committee not later than 180 days after enactment of this Act on its plan to leverage investments made in surface power with its over-arching plan for a sustainable lunar presence into the 2030s. Further, the Committee directs the Space Technology Mission Directorate to utilize existing technology maturation efforts with commercial partners to execute one surface power demonstration by 2026 and provides \$40,000,000 in fiscal year 2023 to begin this initiative. Funds provided for this demonstration shall be used for both payload development and for associated delivery services to the lunar surface via the Commercial Lunar Payload Services program

POWER

The key commodity needed to exploit the Lunar Surface



Equatorial Illumination Limits

- Cyclical periods of 14 days illuminated, 14 days dark
- Consistent

Illumination

The scarce resource needed to produce power

Polar Illumination Limits

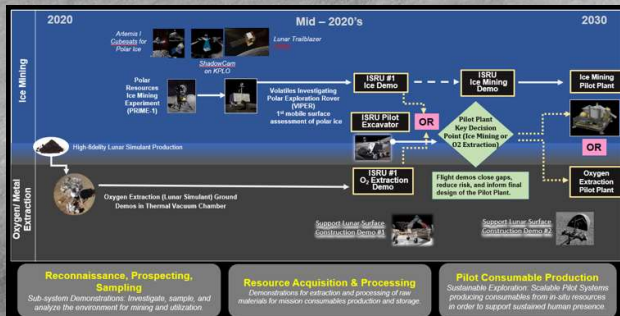
- Intermittent with up to 100 hours darkness
- Highly dependent on location/elevation

In-Situ Resource Utilization (ISRU) is the “Killer App” for Surface Power



Production of propellant from in-situ resources is the demand driver for power at the Lunar South Pole

- Prospecting and tradeoff results will determine whether ISRU propellant will be oxygen from regolith or hydrogen and oxygen from ice mined from permanently shadowed regions. Decision drives power technology development priorities.
 - ISRU pilot plants for propellant production will be powered from **Artemis Base Camp** resources
 - Polar power demand may reach ~2 MW_e at full industrial scale (**Phase 4**) after handoff from Artemis to commercial investment.
 - ISRU/Construction projections may further drive power demand to GW_e levels as infrastructure expands beyond the Polar region toward the Equator (**Phase 4**).



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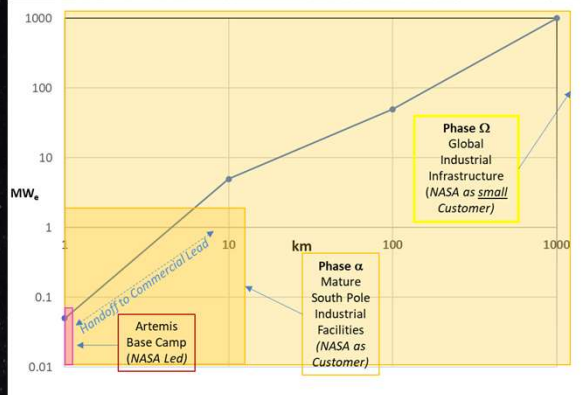
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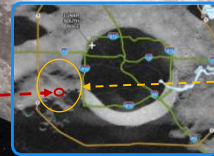
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Envisioned Growth of Lunar Power Infrastructure

STMD advances Technology Building Blocks to enable *Artemis Base Camp** and Phases α and Ω beyond



South Pole Example

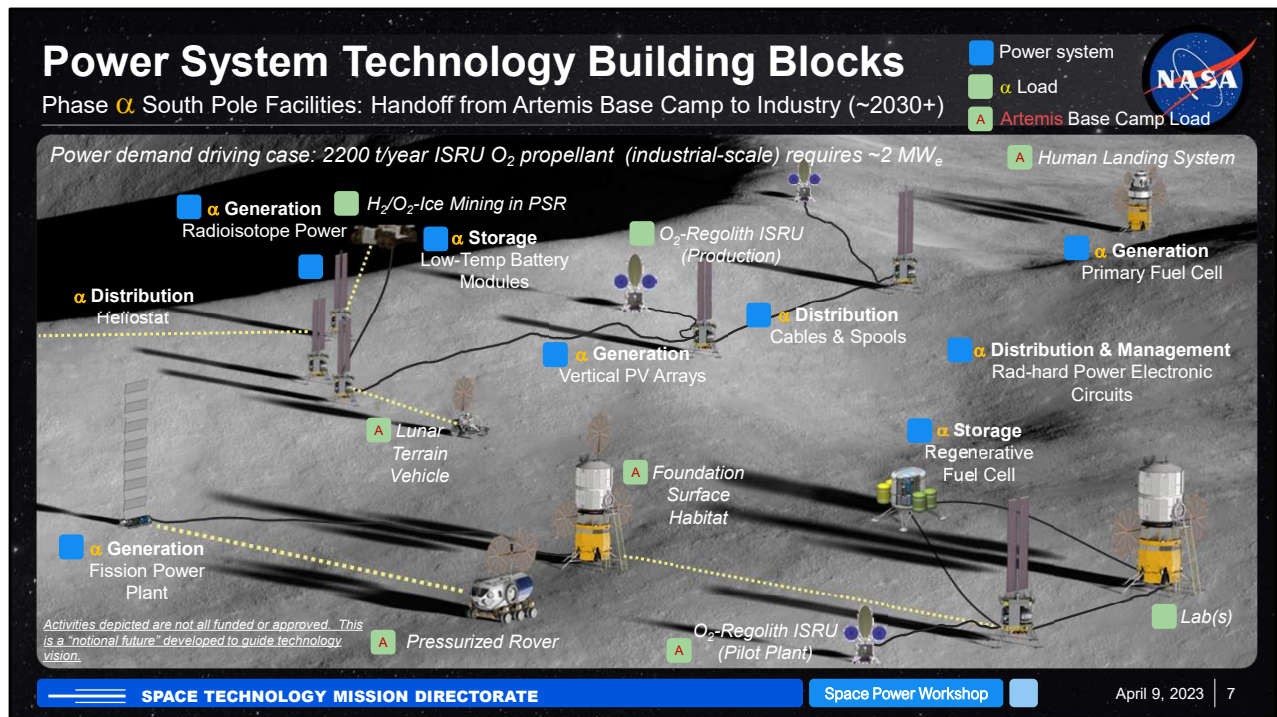


Artemis Base Camp

- ~100 m transmission* (technology risk)
- < 100 kW_e
- May include FSP Nuclear Demo @ 40 kW_e and 1 km transmission

Phase α Polar Industrial-scale Infrastructure

- ca. 2030+
- ISRU Propellant Production @ 2200 mt/year
- ~15 km transmission
- ~2 MW_e (increase from Artemis all solar)



NASA Space Technology Mission Directorate has identified a number of technology building blocks as required to enable this surface power system, whose development is being subsidized by NASA

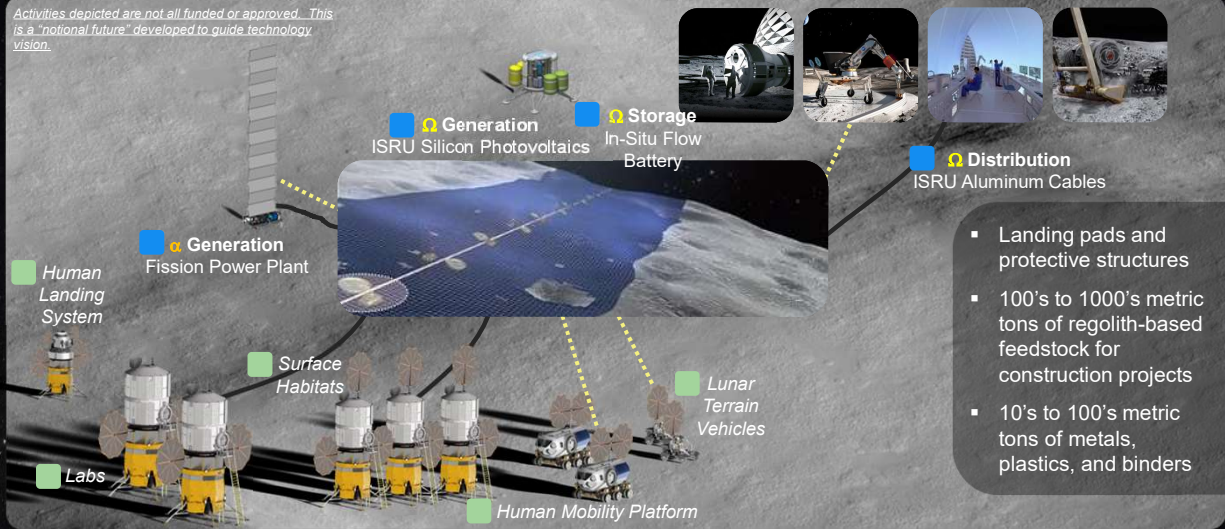
Loads identified with the A are part of the Artemis base camp (each of which has its own independent power source). Other elements are to be delivered by commercial partners to make up the Phase alpha surface system

Power System Technology Building Blocks

Phase Ω : Additional Technology Building Blocks Required to Expand Industrial Activities toward Equator (2040+)



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- Landing pads and protective structures
- 100's to 1000's metric tons of regolith-based feedstock for construction projects
- 10's to 100's metric tons of metals, plastics, and binders

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Further building blocks will be needed to get to the ultimate Phase omega.

STMD Baseline “Envisioned Future Priorities (EFP)”

Guide STMD Investments in Closing Technology Gaps



- Investments prioritized based on projected need dates and difficulty of advancement
 - Highest priority power EFP gap closures support **Artemis Base Camp** and Phase **α** industrial-scale Lunar ISRU production in the early 2030’s at the South Pole
 - Other gap closures support subsequent expansion toward Phase **Ω** construction and ISRU production at lower latitudes in 2040+

Mars Forward

A

Mobile Fission Surface Power

B

Reliable, Rad-Hard Power Conversion and Cable Transmission System

C

Solar Power
Long Life, Grid-Scale Secondary Energy Storage

PSR Operations

D

Wireless Power Transmission
 Low Temperature Secondary Battery Modules
 Radioisotope Energy Sources
 Heliostats and Solar Reflectors
 Superconducting Cable Transmission

Mars Forward

E

CH₄/O₂ Primary Fuel Cell Power

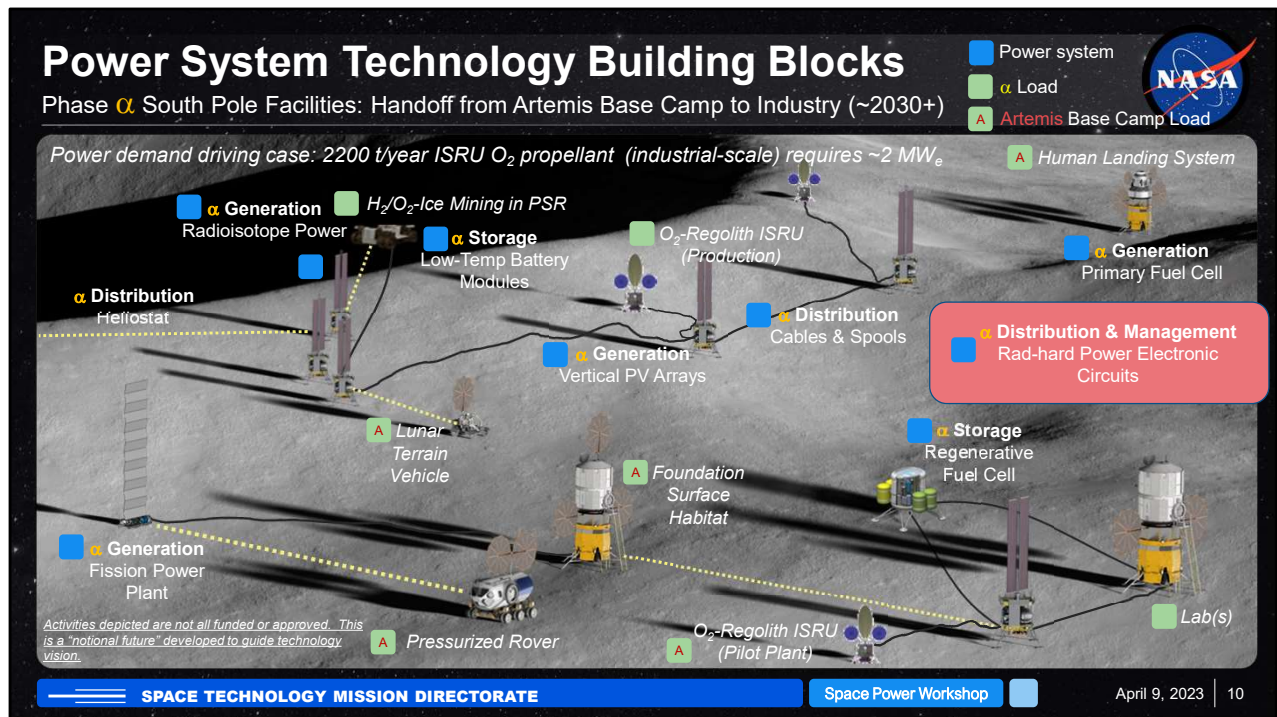
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NASA STMD has prioritized the efforts (“Gap Closures” to bring about the various building blocks. Note Gap D, which includes several items all related to operations in the PSR. Gaps A-C are generic needs for Lunar surface power. Gap E is Mars forward.



None of these building blocks or growth ambitions will do any good if the whole grid goes dark on the first Solar storm. This is where we're going to get bit.

Power electronics which are reliable in the Lunar surface environment thus make up the most important of the technological building blocks.

However, the direction for NASA to enable "Power-as-a-service" means that NASA is not going to be the architect of the grid. Private capital will be.

There are many possible grid topologies, and, as Lunar surface activity grows, the grid will be reconfigured many times. Reliability requirements have a lot of subtle effects on the architecture. The commercial grid provider(s) must select the best configuration at each stage, providing the reliability that power customers demand at the minimum cost.

NASA's role as "first out the gate" customer for power is to:

- Subsidize development of technology to maximize component reliability in the Lunar environment

- Set up a consensus-building community to agree upon design standards for components, interface power quality, and reliability analysis and PRA methods to assess system reliability against customer requirements.

Gap B: Reliable and Efficient Long Distance Power Transmission Systems (Cables and Conversion)



Thrust: LIVE

Outcomes: Sustainable power sources and other surface utilities to enable continuous Lunar and Mars surface operations

Taxonomy Elements: 3.3.1, 3.3.2, 3.3.3, 3.3.4

Definitions:

BA: SOA Earth-sourced power converters, transformers, cables and load connection and deployment systems do not provide capability at specific power, voltage, and radiation-, thermal- and dust-tolerance levels sufficient to support reliable power distribution among Lunar pole surface elements. Flight-qualified technologies for all these components are not adapted the Lunar polar environment.

BB: The technology required to print long distance conductors (100's of km) on the Lunar surface from locally-sourced aluminum has seen little conceptual development.

Mission architects must know what capability will be available to them once full-scale ISRU production operations are to start in the early 2030s and once large-scale Lunar surface operations expand toward the lower latitudes in the late 2030s.

SOA: Power converters of sufficient reliability for current missions are at TRL 9 for near- Earth, geosynchronous, and deep space missions at <200 V. Cables, dust-tolerant load connection systems, and cable deployment systems for the Lunar surface have been developed only to the "bench-top" level. Terrestrial microgrid topologies of similar capacity are well understood.

Gap B (α) Closure:

Bring to TRL 6 by 2030 power conversion and cable transmission systems which can (a) invert/boost (b) transmit (c) buck/rectify power between low voltage sources and loads (120 -200 VDC) at a 10 kW_e-scale up to 10 km, transmitting at:

- ~1000-1500 VDC or at:
- ~3000+ VAC, 1 kHz

The systems must lose no more than 3% per km in transmission, must maximize specific power, and must be able to operate at >0.95 power factor and 0.99 reliability for 10 years in the relevant Lunar radiation, dust, and thermal environments and in the Lunar hard vacuum and Mars atmosphere environments.

Closure Roadmap (α):

- LuSTR or ECF project for integrated subsystem (material, device, circuit) reliability modeling/prediction/verification.
- Further SBIR/ESI efforts for dust tolerant load connection, radiation-hard electronics, and cable/spooling systems
- Continue both MIPS and TYMPO GCD efforts to bring 0.99 reliability converter/transformer/rectifier systems to TRL 6
- TDM projects to demonstrate components (cable/spool, connectors, proximity charging) on CLPS and at Artemis Base Camp



Gap B (β) Closure:

Bring to TRL 6 by 2035 MW_e, 100 km-scale power transmission systems with conductors printed on the Lunar surface from Lunar-sourced aluminum and with minimal material brought from Earth.

Closure Roadmap (β):

- STRG and SBIR efforts for Lunar aluminum mining and conductor printing
- GCD efforts to bring integrated, printed power conductor systems to TRL 6 by 2035
- TDM project to fly and operate power conductor production equipment on the Lunar surface by 2037

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The high priority Gap defined for power transmission is closed by technology efforts in:

- Semiconductors
- Converter circuit design (AC vs DC)
- Cable design
- Connector design

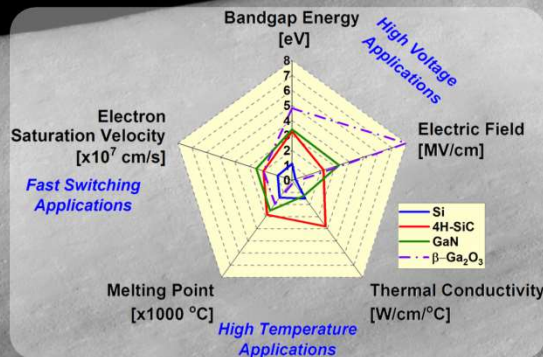
All tolerant of the Lunar surface environment (radiation, temperature, dust) with maximum prior reliability with a narrow distribution.

Wide Band Gap Semiconductors



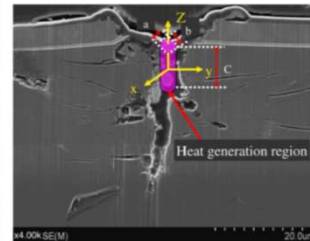
Performance of Wide-Band-Gap semiconductors at high-V in Lunar radiation environment is not fully understood

- High voltages (AC or DC) needed to transmit power over long distances.
- Advanced development efforts on hi-voltage WBG components to date are limited.



"Achilles' Heel" of Wide Band Gap Materials:
Single Event Effects(SEE)

SiC Diode



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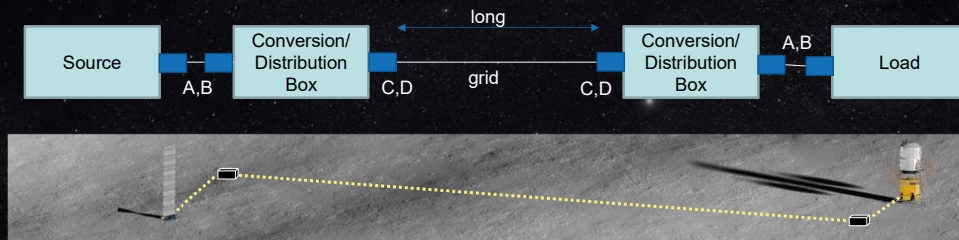
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- The "achilles heel" of WBG semiconductor devices is SEE. NASA is funding development efforts in Si-C, GaN, Ga₂O₃ and diamond to determine which offers the best combination of properties and availability. Note that NASA's demand is so small as to have little influence on the availability.

Evolvable Lunar Surface Power Grid



Basic Module



Bidirectional Power Quality to be standardized at multiple interfaces

- A. LV at Loads ($< 200\text{ V}$)
- B. HV for Transmission ($> 1\text{ kV}$? AC vs. DC?)
- C. Mid V (?) for Sources

The Reliability of a Lunar Surface Power Grid hinges on the Reliability of its Convertors

WBG Devices are more radiation tolerant (reliable) at low voltages. This calls for a trade between AC and DC for long distance transmission.

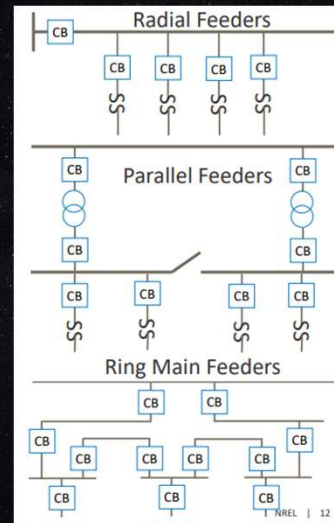
- Convertors operating at low voltage can be combined with AC transformers to make a low frequency (50Hz to $\sim 2\text{ kHz}$) grid.
- Alternatively, Low voltage converters can also be combined in redundant series arrays to get high DC voltages. This would allow a DC grid.
 - Terrestrial HVDC lines often use a similar redundancy scheme.

This trade needs to be made on reliability as well as on specific power and will inform power quality standards at the various interfaces in the grid.

Evolvable Lunar Surface Power Grid



Reliability requirements will drive the selection of the topologies into which the grid modules will be combined as the system grows



This will in turn inform the choice of optimal topology as the power grid grows.

System/Grid Reliability Requirements



Reliability requirements and, therefore, ultimate system design & verification requirements must be viewed differently for the industrial scale Lunar surface power system than for previous crewed spacecraft.

Historic Crewed Spacecraft

(e.g., International Space Station, Space Shuttle)

- Multi-kW_e-scale, unidirectional DC systems
- Component/Device experience base too small for useful PRA conducted from posterior reliability assessments.
- LEO environmental effects insufficiently understood for useful prior reliability analyses for components
- Most loads considered "critical"
- Reliability guaranteed by fault tolerance

Terrestrial Power Grids

(e.g., Texas grid managed by ERCOT)

- Multi-GWe-scale AC systems fed by rotating equipment are dominant, but inverter-fed bi-directional grids growing.
- Component/device experience base in terrestrial environments adequate for high-confidence posterior reliability assessments.
- Most loads not considered "critical".
- Reliability guaranteed by fault tolerance for critical loads
- PRAs conducted on expansion from legacy grids used to negotiate reliability requirements with customers with non-critical loads.

NASA Artemis Elements

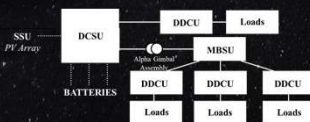
(e.g., Orion, SLS, HLS)

- Multi-kW_e-scale unidirectional DC systems.
- Component/device experience base in low-voltage space applications adequate for high-confidence posterior and (sometimes) prior reliability assessments.
- Most loads considered "critical".
- PRAs conducted to negotiate mission-level LOC/LOM requirements, enabling zero-fault tolerant system for some critical loads.
- Reliability guaranteed by fault tolerance for most critical loads

Lunar Surface Grid

(Artemis Base Camp? Phase α? Phase Ω?)

- Project multi-MW_e-scale, bidirectional, inverter-fed, hybrid AC/DC systems
- Component/device experience base in high-voltage space applications in adequate for high-confidence posterior reliability assessments. Enforce design standards enabling prior reliability assessments (?)
- Few loads considered "critical".
- Conduct PRAs to negotiate reliability requirements for non-critical loads, enabling zero-fault tolerant system for some critical loads.
- Reliability guaranteed by fault tolerance for critical loads on crewed systems.



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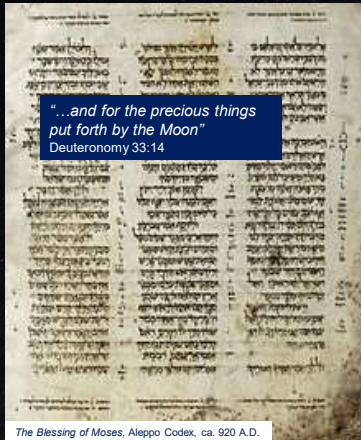
Trades on devices, components, modules, and topologies all roll up into a system reliability assessment.

Reliability management for the future Lunar surface power system may be a combination of the Artemis element paradigm and terrestrial grid paradigm.

Reliability requirements will have be negotiated across a diverse community of source providers and load customers.

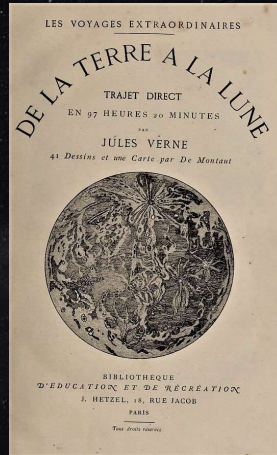
Much more study to be done.

Lunar Surface Infrastructure will bring the benefits of the Moon to all Mankind.



The Blessing of Moses, Aleppo Codex, ca. 920 A.D.

ca. 1000 B.C.



1865



2065 ?

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Oldest surviving human writings refer to the Moon as a light or sign but also as a source of riches.

In 1865, When Jules Verne sat down in Paris to write the book that kicked off the space age, reasonable people still believed there might be life on the Moon.

Maybe by the bicentennial of Verne's book, there will be life on the Moon and riches untold found.