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

Toward an Electric Power Utility on the Lunar Surface

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

John H Scott | Principal Technologist, Power and Energy Storage, Space Technology Mission Directorate | June 20, 2023

NASA Moon2Mars Architecture: Strategy and Objectives

- **Human Lunar Return**
- **Foundational Exploration**
- **Sustained Lunar Evolution**
- **Humans to Mars**

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 an initial human Mars exploration campaign

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

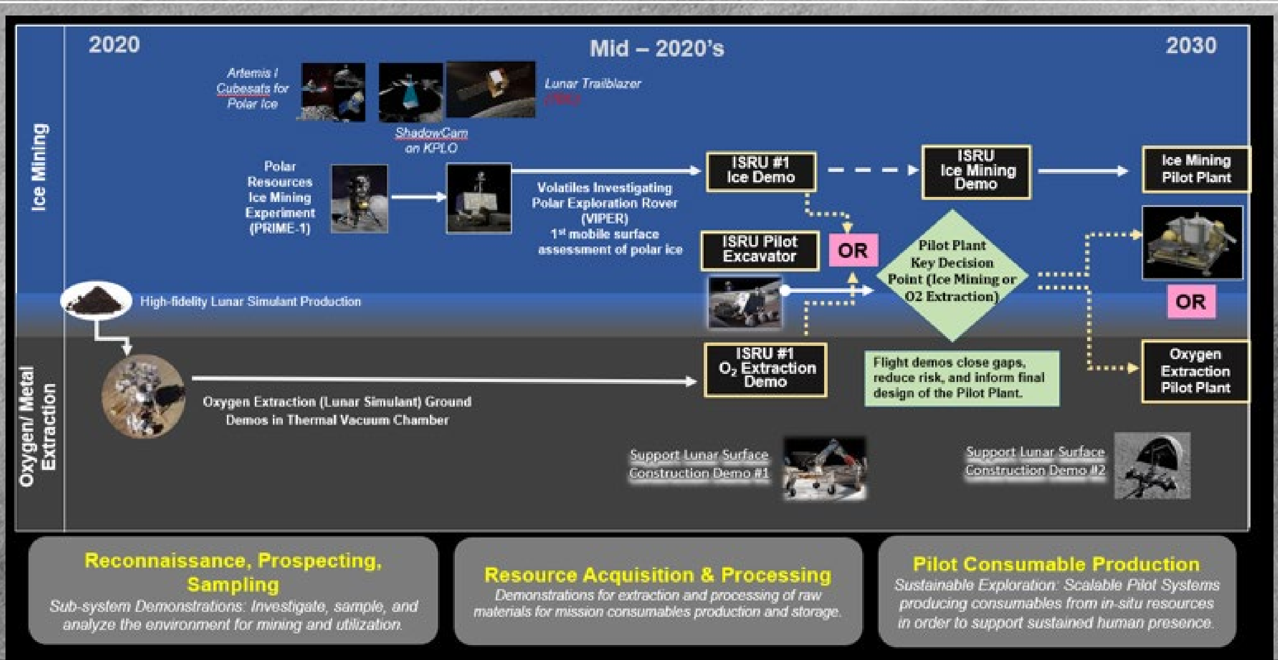
Polar Illumination Limits

- 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 in-situ resources is the demand driver for power at the Lunar South Pole

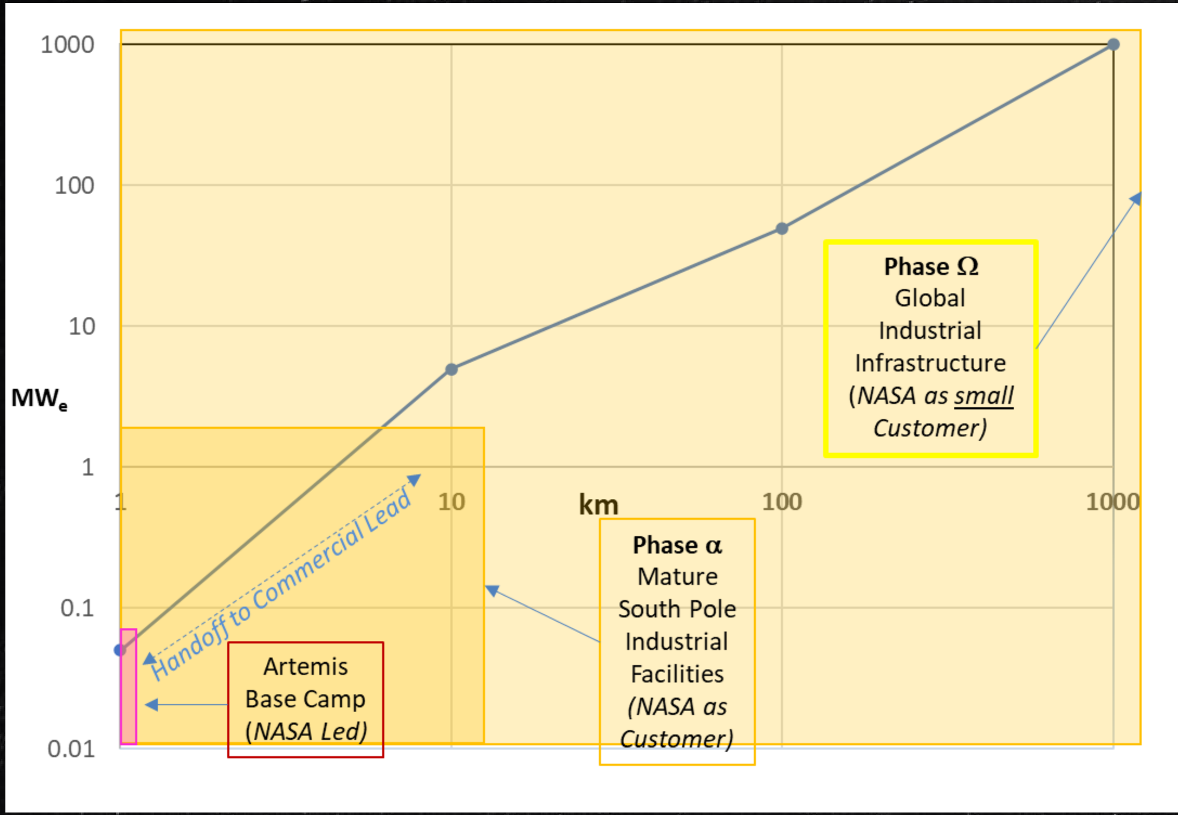
- *Prospecting and tradeoff results will determine whether ISRU propellant will be oxygen from regolith or hydrogen and oxygen from ice mined from permanently shadowed regions. Decision drives power technology development priorities.*
    - *ISRU pilot plants for propellant production will be powered from Artemis Base Camp resources*
    - *Polar power demand may reach ~2 MW_e at full industrial scale (Phase α) 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 Ω).*



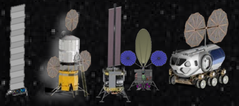
Activities depicted are not all funded or approved. This is a "notional future" developed to guide technology vision.

Envisioned Growth of Lunar Power Infrastructure

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

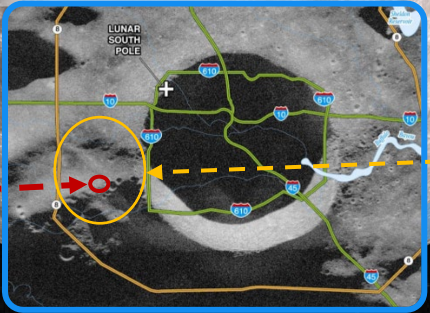


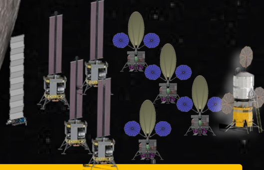
Phase Ω: Global Industrial Infrastructure
- *ca. 2040+*
- *ISRU and facilities construction*
- *~1000 km transmission*
- *~1+ GW_e*



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

South Pole Example



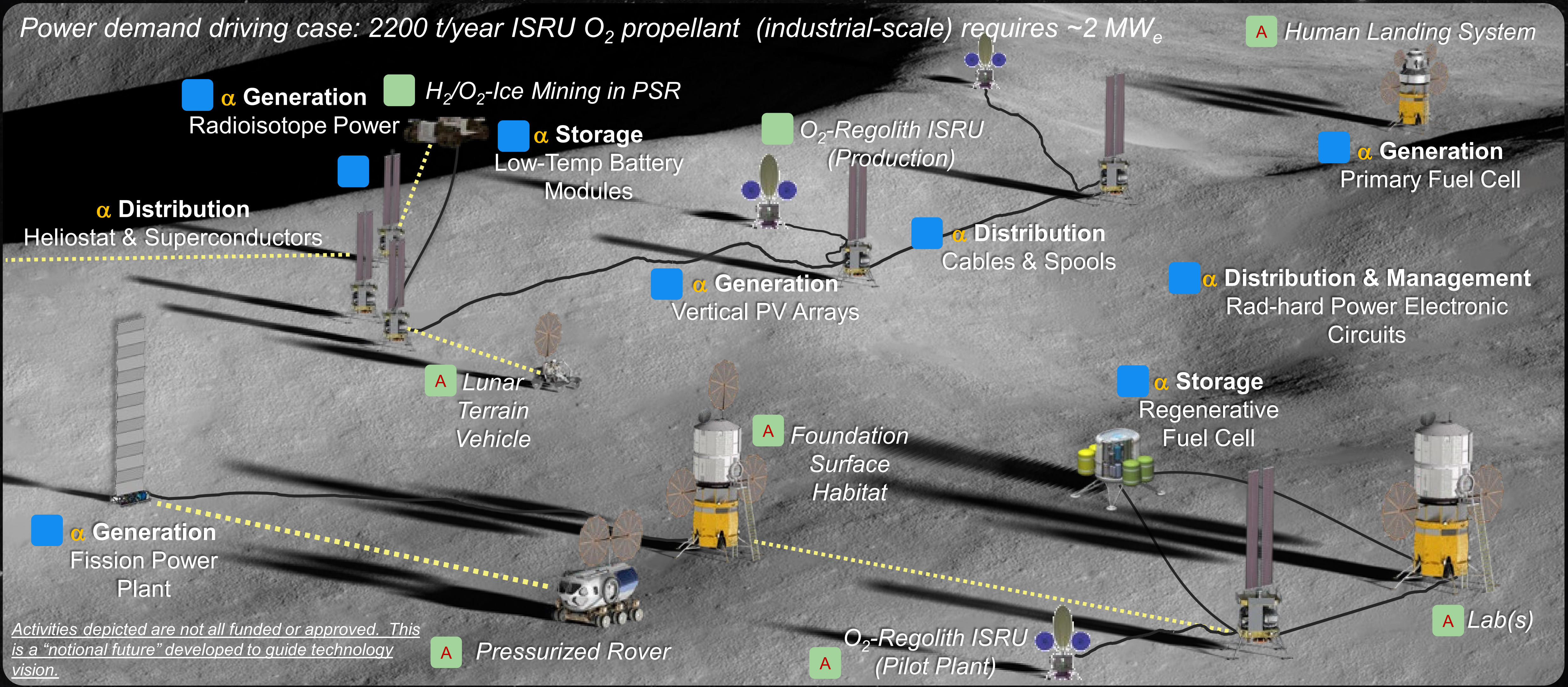


Phase α: Polar Industrial-scale Infrastructure
- *ca. 2030+*
- *ISRU Propellant Production @ > 2000 mT/year*
- *~15 km transmission*
- *~2 MW_e (increase from Artemis all solar)*

Power System Technology Building Blocks

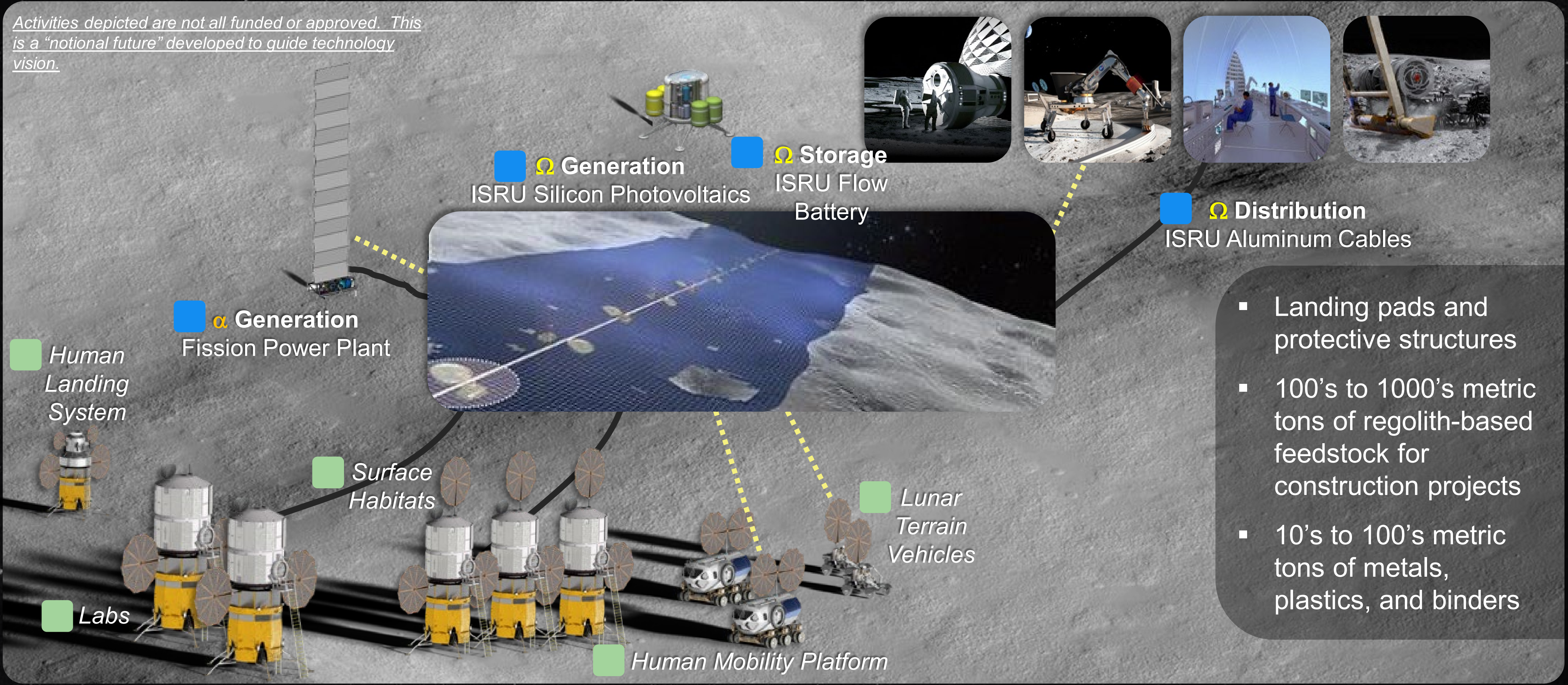
Phase α South Pole Facilities: Handoff from Artemis Base Camp to Industry (~2030+)

- Power system
- α Load
- A Artemis Base Camp Load



Power System Technology Building Blocks

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



- 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

STMD Baselined "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+**

A — *Mars Forward*

Mobile Fission Surface Power

B

Reliable, Rad-Hard Power Conversion and Cable Transmission System

C

Solar Power

Long Life, Grid-Scale Secondary Energy Storage

D — *PSR Operations*

Wireless Power Transmission

Low Temperature Secondary Battery Modules

Radioisotope Energy Sources

Heliostats and Solar Reflectors

Superconducting Cable Transmission

E — *Mars Forward*

CH_4/O_2 Primary Fuel Cell Power

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Power System Technology Building Blocks

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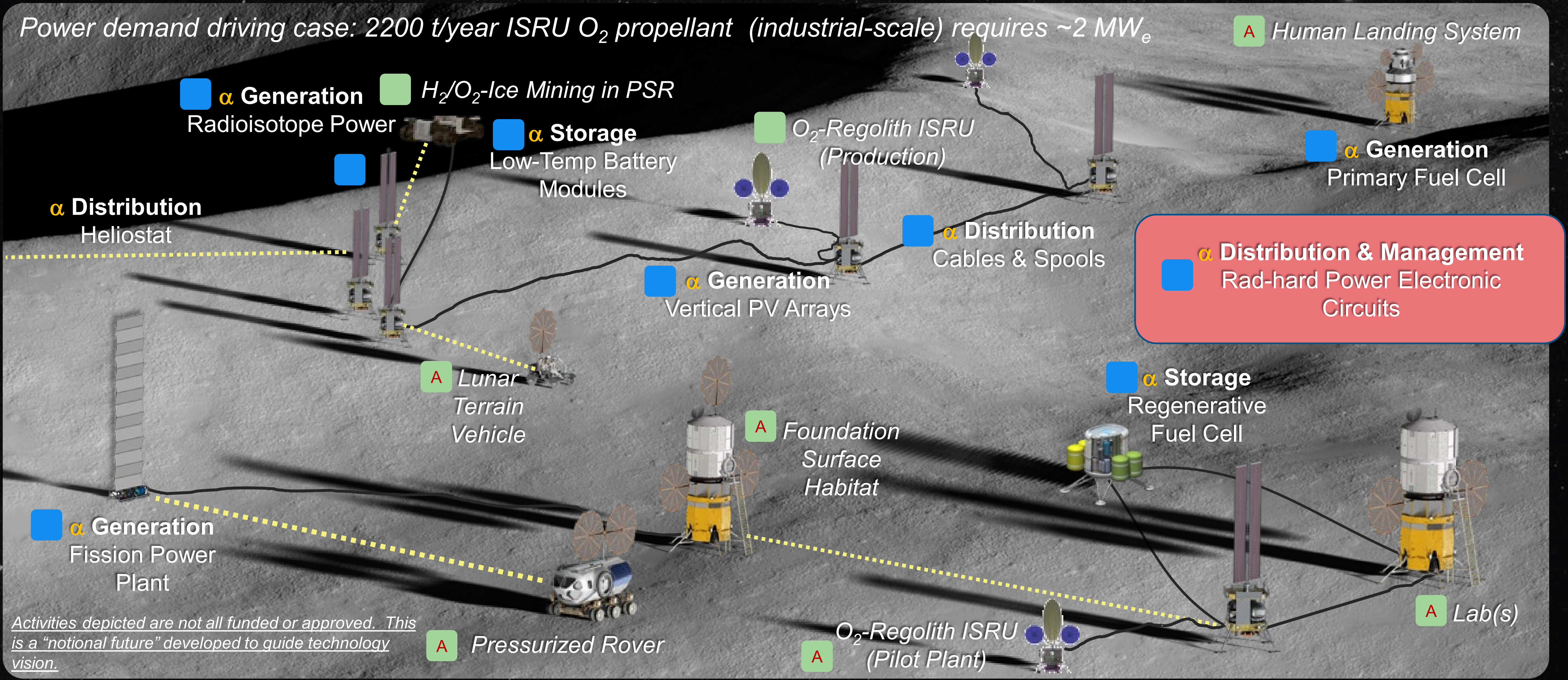

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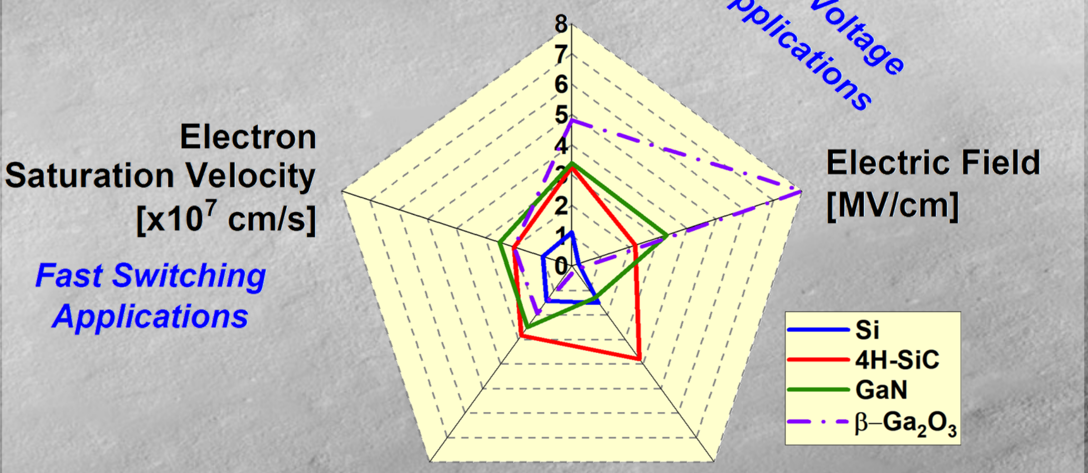
Wide Band Gap Semiconductors

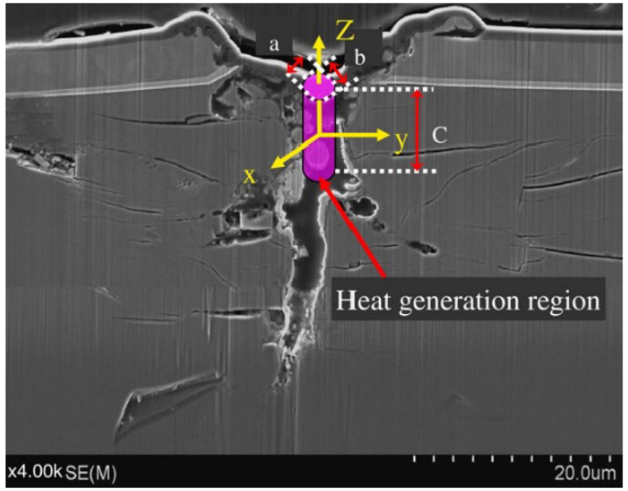
Performance of Wide-Band-Gap semiconductors at high-V in Lunar radiation environment is not fully understood

- 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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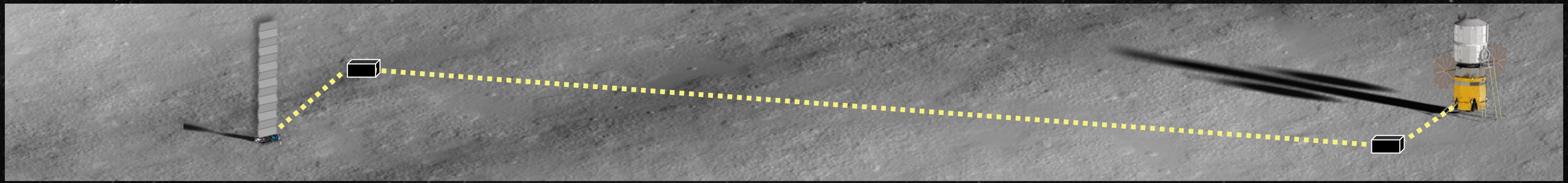
Evolvable Lunar Surface Power Grid

Basic Module



Bidirectional Power Quality to be standardized at multiple interfaces

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

The reliability of a Lunar surface power grid hinges on the reliability of its convertors

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

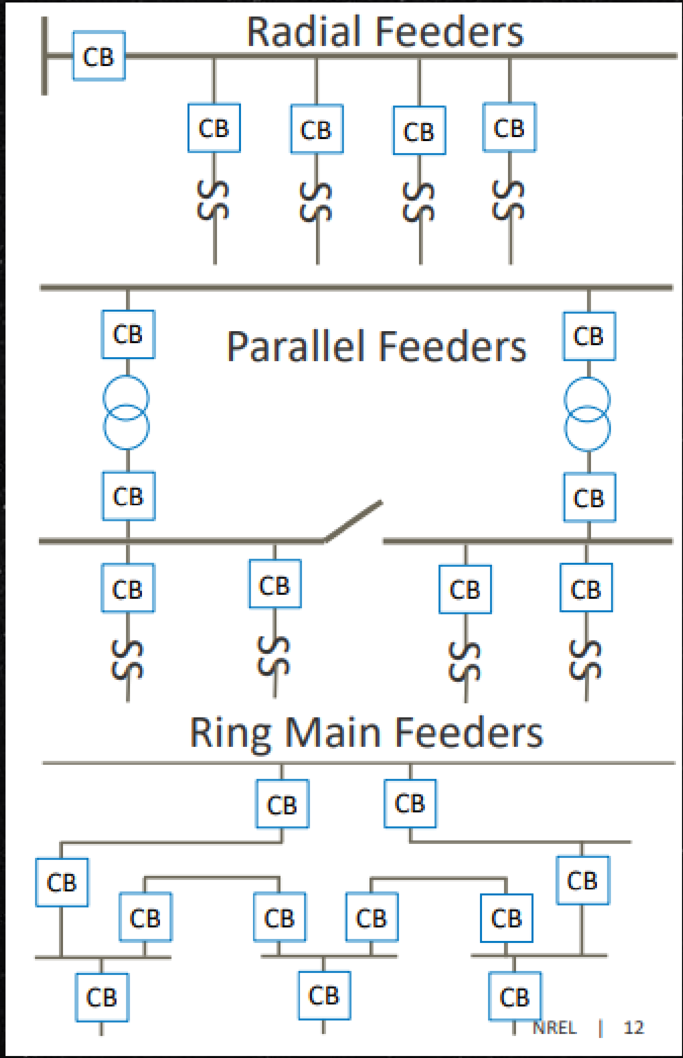
Gap B (Ω) Closure:
Bring to TRL 6 by 2035 MW_e-, 100 km-scale power transmission systems with conductors printed on the Lunar surface from Lunar-sourced aluminum and with minimal material brought from Earth.

Closure Roadmap (Ω):

- *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*

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



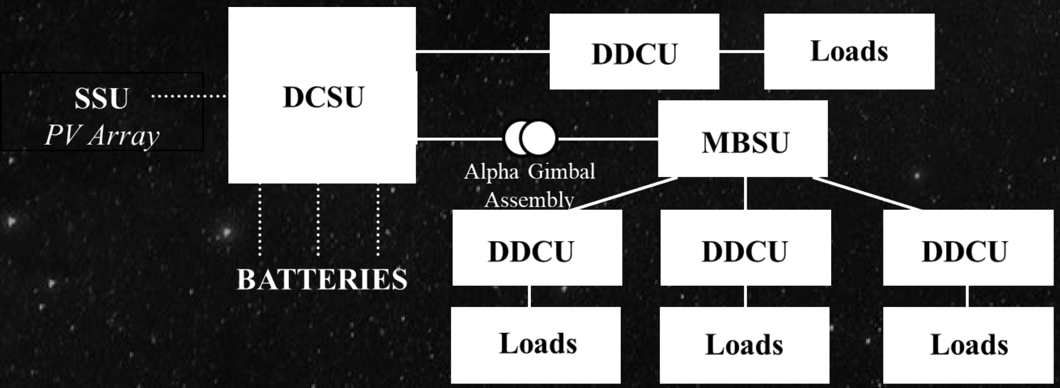
System/Grid Reliability Analyses

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

Historic Crewed Spacecraft

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

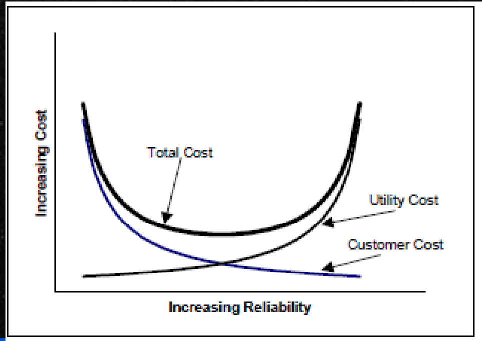
- Multi-kW$_e$-scale, unidirectional systems <150 VDC
- Failures driven by LEO radiation environment
- Component/Device experience base too small for useful PRA based on posterior reliability assessments.
- Most loads considered “critical”
- Reliability guaranteed by fault tolerance



Terrestrial Power Grids

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

- Multi-GW$_e$-scale kVAC systems fed by rotating equipment are dominant, but inverter-fed bi-directional grids are growing.
- Failures driven by weather and human error. 98% of failures due to distribution or transmission; 2% to generation
- Component/device experience base in terrestrial environments (e.g., IEEE standards) adequate for high-confidence PRAs.
- Loads have varying degrees of “criticality”
- PRAs conducted on expansions from legacy grids used to verify reliability compliance (e.g., 99.9% = 9 hrs/yr down), often with fault tolerance for higher criticality loads



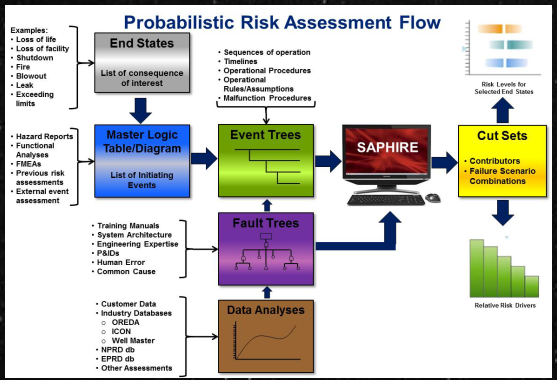
System/Grid Reliability Analyses

Artemis program engaging modern reliability analyses. New reliability assessment paradigm needed for a Lunar surface grid.

NASA Artemis Elements

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

- Multi-kW$_e$-scale mostly unidirectional systems (some bidirectional) < 150 VDC.
- Component/device experience base in low-voltage space applications adequate for high-confidence posterior and prior reliability assessments.
- Most loads considered “critical”.
- PRAs conducted to negotiate mission-level LOC/LOM requirements
- Reliability guaranteed by fault tolerance for most critical loads



Lunar Surface Grid

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

- Multi-MW$_e$-scale, bidirectional, inverter-fed, hybrid AC/DC systems up to 1500 VDC or 3000 VAC 1 kHz are projected
- Component/device experience base in high-voltage and deep space environment are inadequate for high-confidence posterior reliability assessments.
- New component design standards enabling prior reliability assessments are required
- Many loads not considered “critical”.
- PRAs needed to negotiate reliability requirements for non-critical loads
- Reliability guaranteed by fault tolerance for critical loads in crewed systems, but how much redundancy?

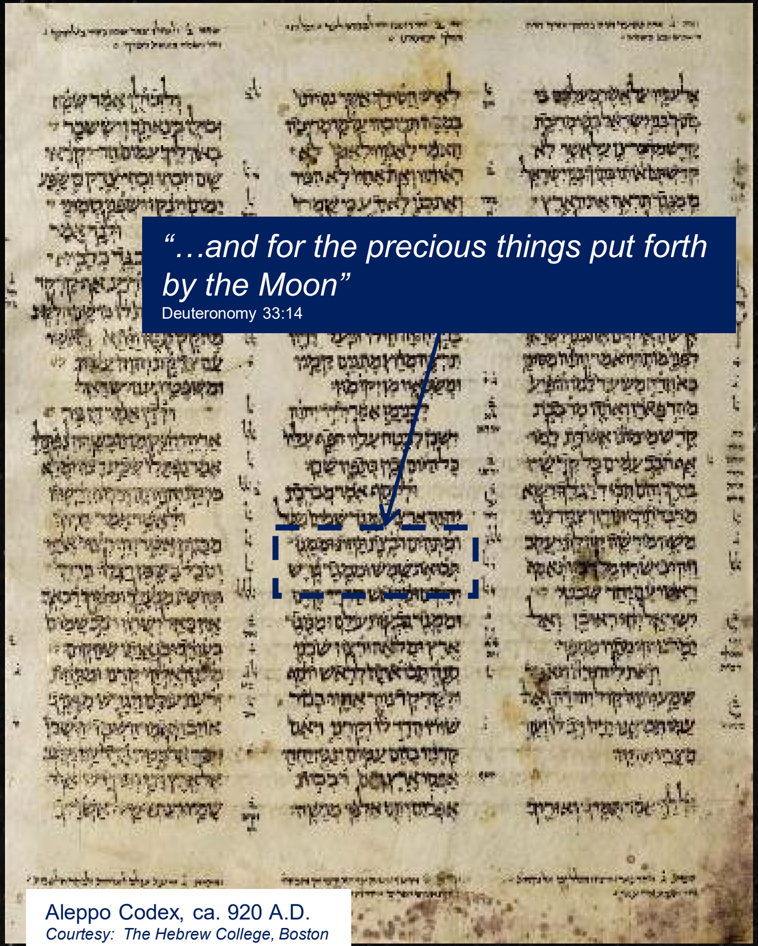
Lunar Surface Innovation Consortium (LSIC)

The LSIC, facilitated through the Johns Hopkins University Applied Physics Lab (APL), is a nationwide alliance of universities, industry, non-profit research institutions, NASA, and Other Government Agencies with a vested interest in our nation's campaign to establish a sustained presence on the Moon.

Surface Power Reliability Workshop (Virtual)
26-27 July 2023

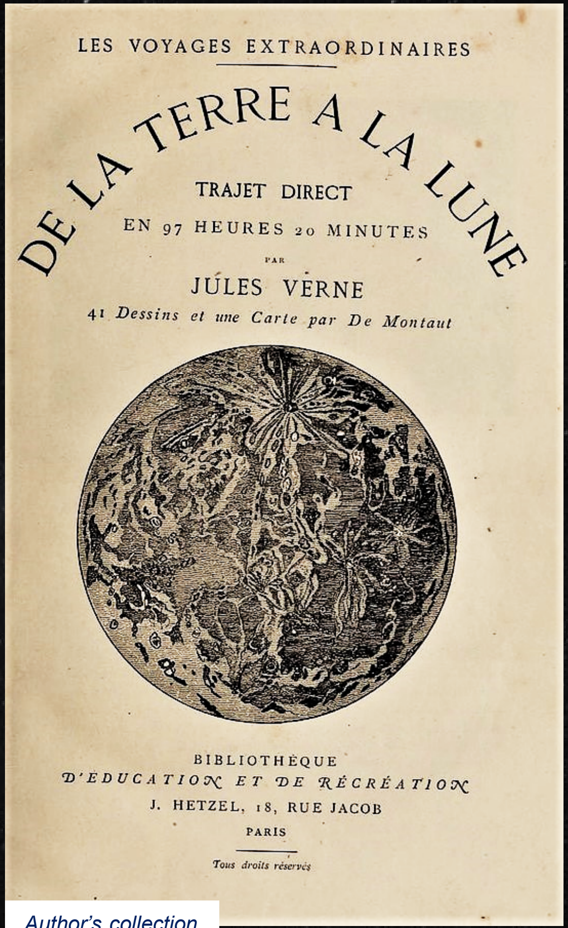
https://lsic.jhuapl.edu/Our-Work/Focus-Areas/index.php?fg=Surface-Power

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



Aleppo Codex, ca. 920 A.D.
Courtesy: The Hebrew College, Boston

1st/2nd millennium B.C.


LES VOYAGES EXTRAORDINAIRES

DE LA TERRE A LA LUNE

TRAJET DIRECT

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PAR

JULES VERNE

41 *Dessins et une Carte par De Montaut*

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