

Electrifying the Moon

Jeffrey Csank

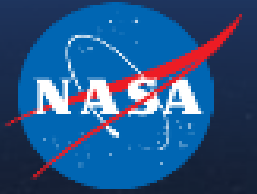
Surface Systems Integration, Power Lead

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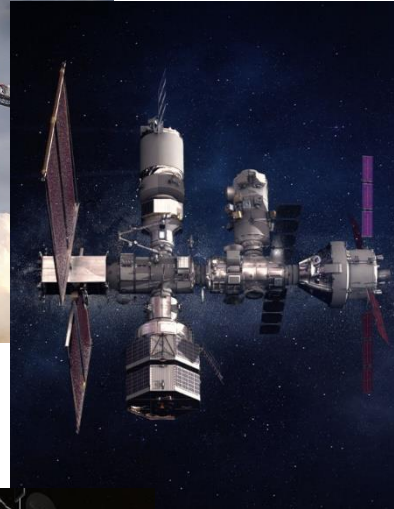
Cleveland, OH



**Interagency Advanced Power Group (IAPG)
Combined Electrical Systems and Mechanical Working Groups
University of New Hampshire
Durham, NH
June 6-8, 2023**

- **Artemis Program**

- Reestablish a human presence on the lunar surface
 - First woman and first person of color on the Moon
 - Establish the first long-term presence on the Moon
 - Take the next giant leap – Human on Mars
- Artemis Missions
 - ✓ • Artemis I (2022) : uncrewed test of SLS and Orion
 - *Artemis II: first crewed test flight of SLS and Orion*
 - *Artemis III: first crewed lunar landing*
 - *Artemis IV: second crewed lunar landing*
 - *Artemis V–VIII: TBD*



Moon to Mars (M2M) Objectives



Lunar Infrastructure (LI) Goal: Create an interoperable global lunar utilization infrastructure where U.S. industry and international partners can maintain continuous robotic and human presence on the lunar surface for a robust lunar economy without NASA as the sole user, while accomplishing science objectives and testing for Mars.

- **LI-1L:** 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) Goal: Create essential infrastructure to support initial human Mars exploration campaign.

- **MI-1M:** Develop Mars surface power sufficient for an initial human Mars exploration campaign.

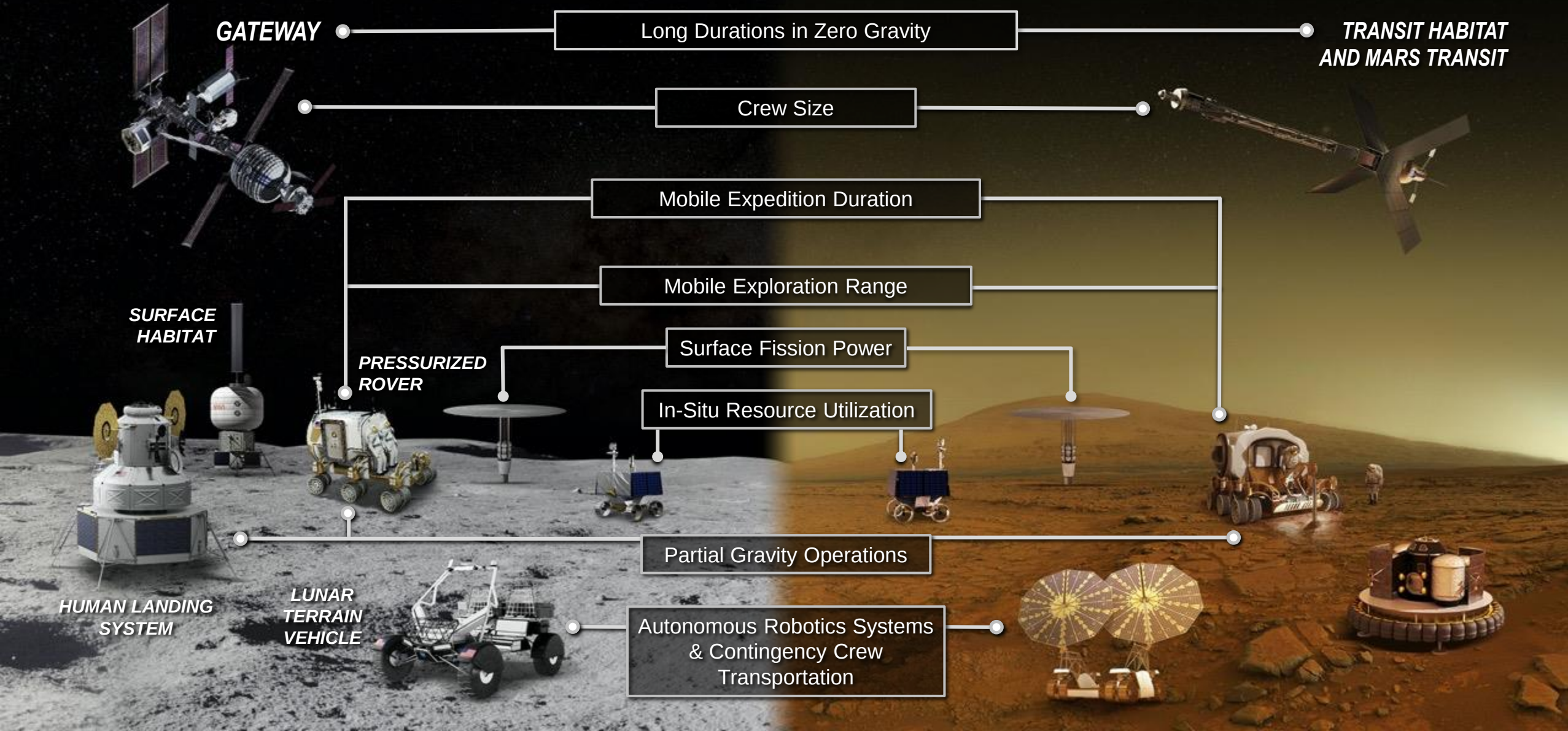
INFRASTRUCTURE OBJECTIVES

Lunar
Mars



Moon to Mars Exploration

Operations on and around the Moon will help prepare for the first human mission to Mars



The Moon



- **Size:**

- Equatorial radius of 1,738.1 km, ~ 0.2725 of Earth
 - 5th largest moon in our solar system
 - Largest moon in solar system relative to size of the planet

- **Orbit period / length of day**

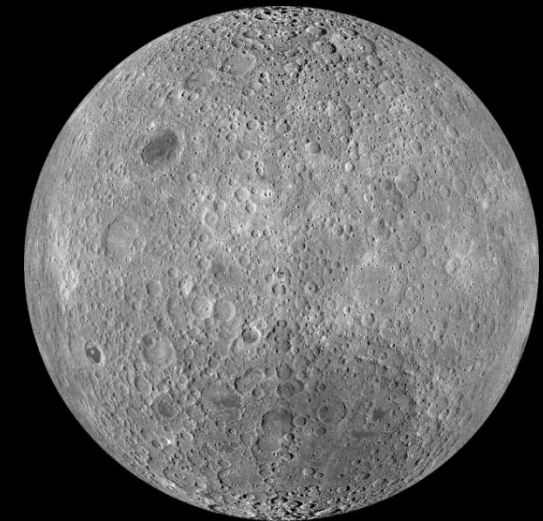
- 27 days
- Earth and moon are tidally-locked
 - Earth will only see one side of the moon

- **Exploration**

- More than 105 robotic spacecraft missions
- Only celestial body beyond Earth visited by Humans
 - Last time visited in December 1972



Near Side

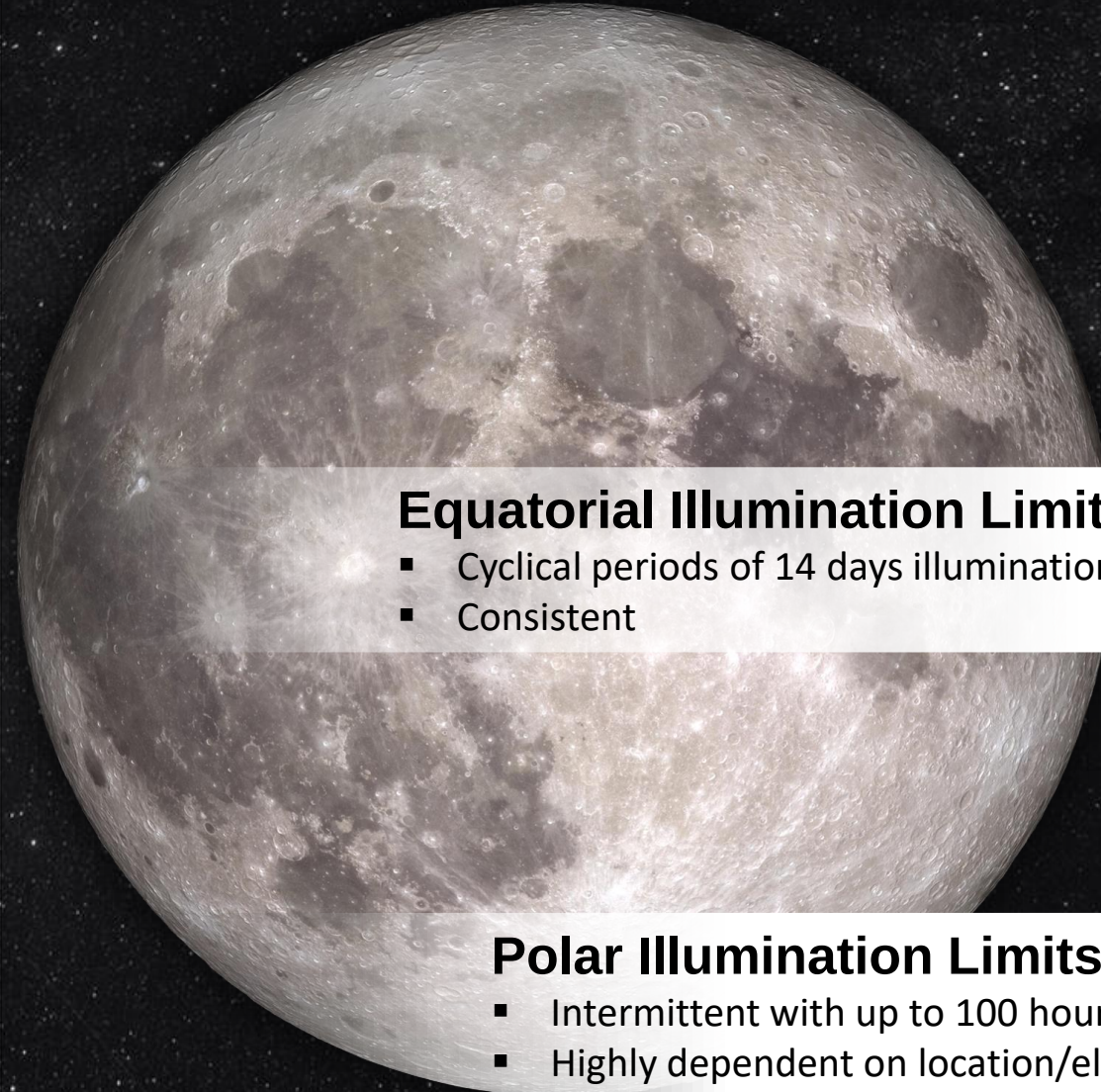


Far Side



Illumination

The primary and scarce *resource* needed to produce power



Equatorial Illumination Limits

- Cyclical periods of 14 days illumination, 14 days darkness
- Consistent

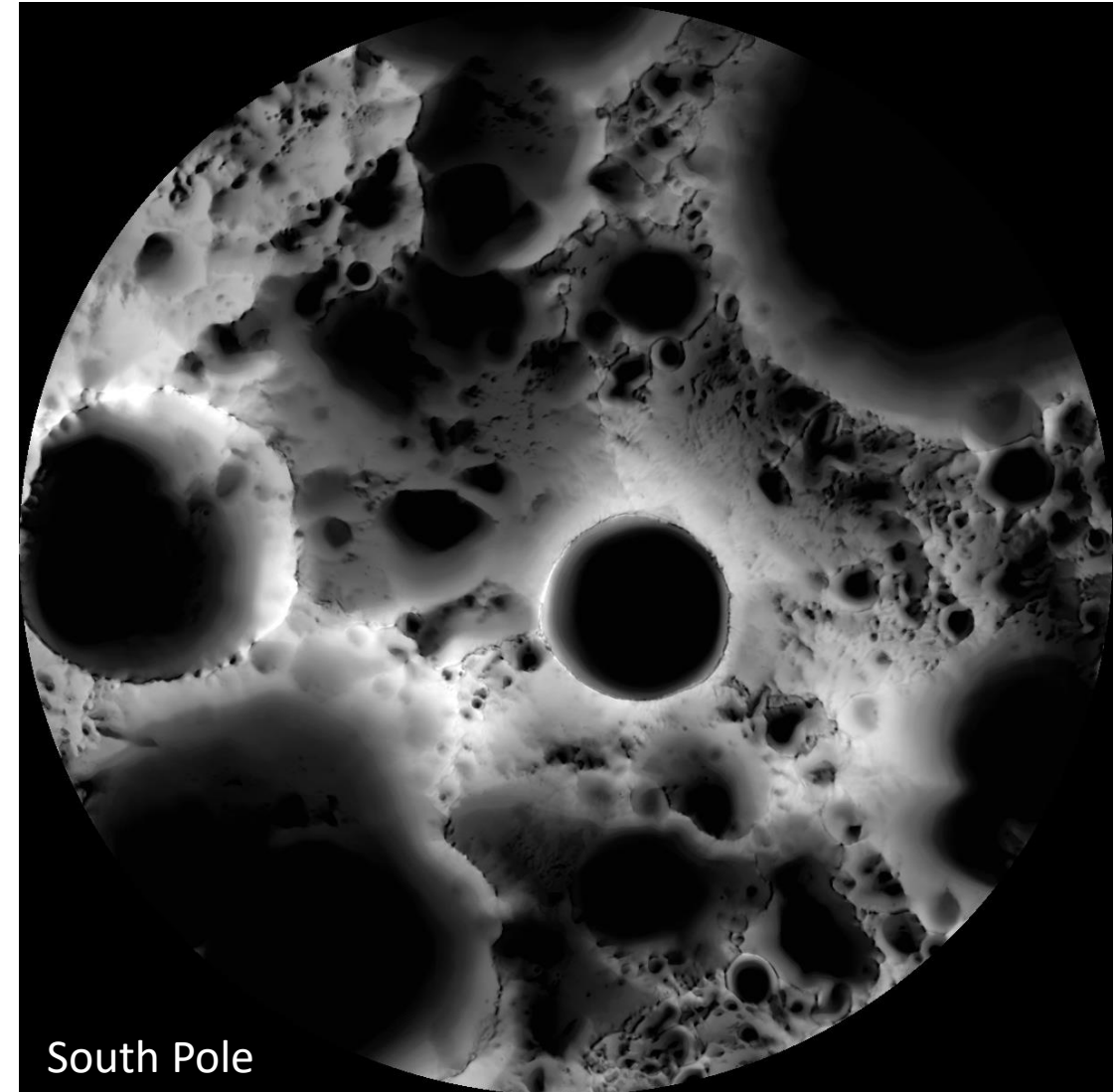
Polar Illumination Limits

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

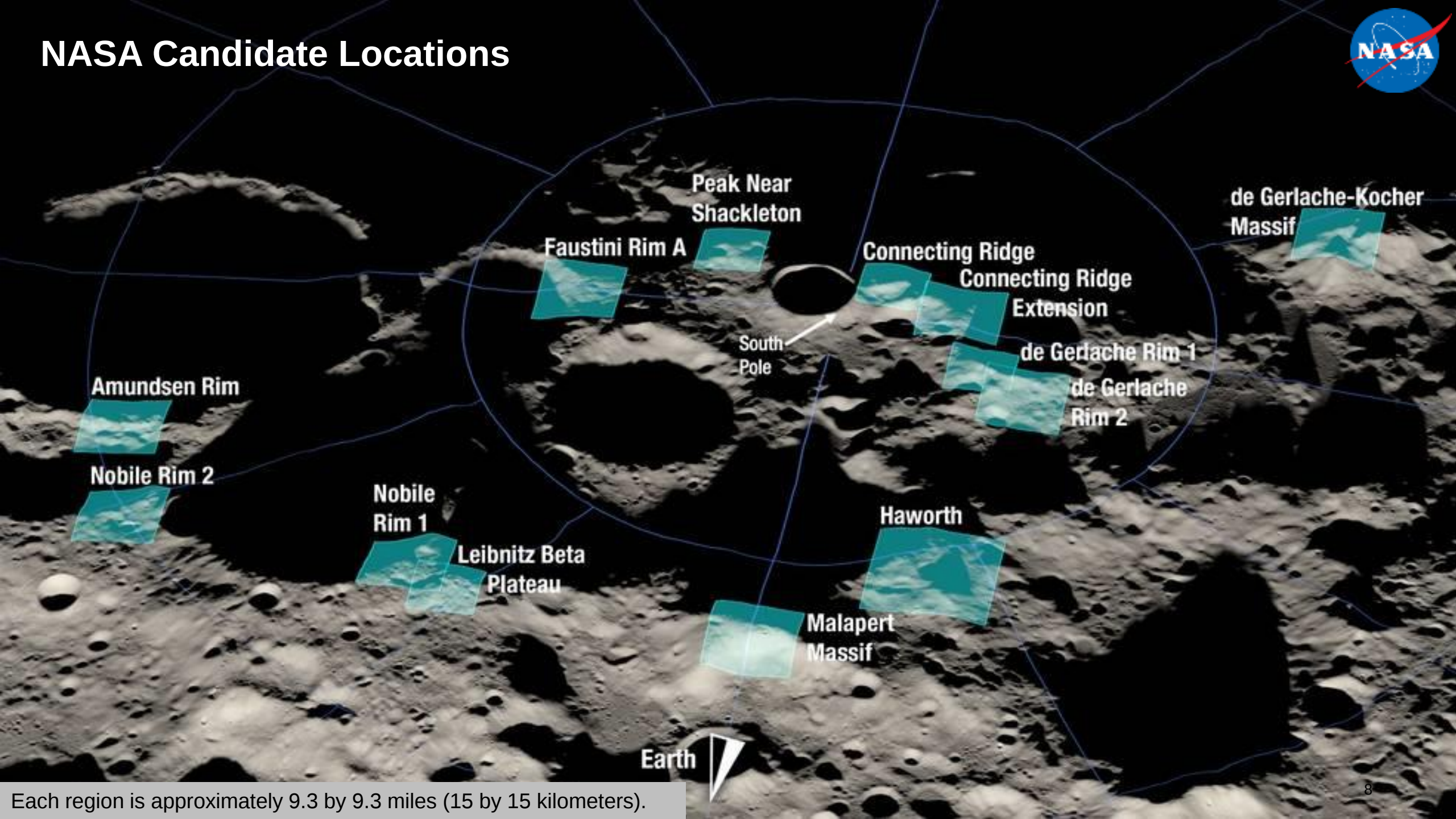
Polar Landing Site Selection



- **Constant Light and Power**
 - Crater rims in almost continuous sunlight
 - 80 – 90% year-round sunlight (South Pole)
 - Decrease energy storage requirements (eclipse)
 - Maximize lunar surface operations
- **Water on the Moon**
 - In-situ resource utilization (ISRU)
 - Fuel for landers
 - Lunar Science
 - Permanently shadowed regions (PSRs)
 - Average temperature -183°C
 - Temperature never exceeds -173°C
 - Any water vapor that arrived at the lunar surface from comets or meteorites would have been trapped



NASA Candidate Locations



Earth

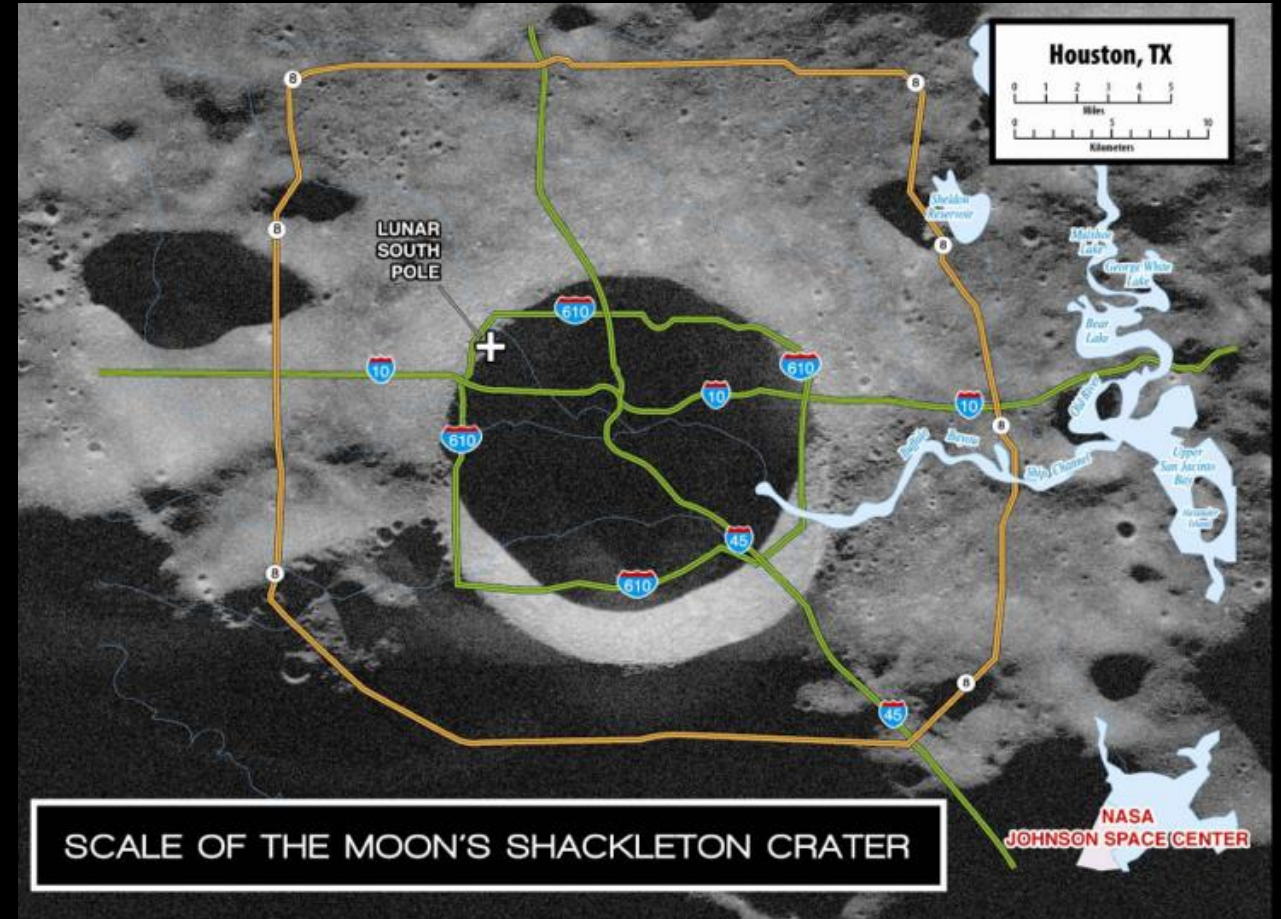
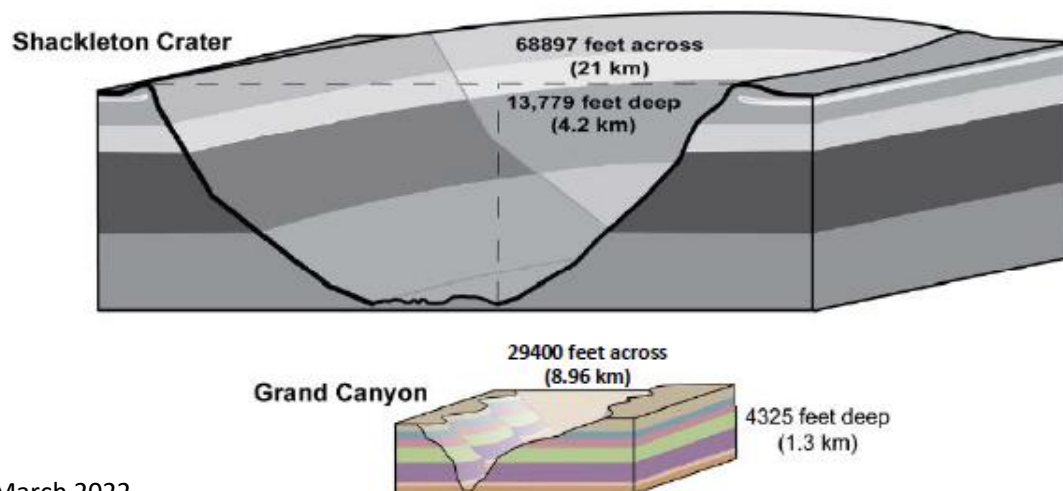
Each region is approximately 9.3 by 9.3 miles (15 by 15 kilometers).

Shackleton Crater



- ~20 km in diameter
- ~4 km deep and ~3x deeper and wider than the Grand Canyon at Enfilade Point
- Located at Lunar South Pole
- Rim and Connecting Ridge are primary targets for future lunar landings

SHACKLETON CRATER vs. GRAND CANYON



Artemis Base Camp Zone

Artemis Power System



ARTEMIS



Artemis Base Camp Buildup

First lunar surface expedition through Gateway; external robotic system added to Gateway; Lunar Terrain Vehicle delivered to the surface

Sustainable operations with crew landing services; Gateway enhancements with refueling capability, additional communications, and viewing capabilities

Pressurized rover delivered for greater exploration range on the surface; Gateway enables longer missions

Surface habitat delivered, allowing up to four crew on the surface for longer periods of time leveraging extracted resources. Mars mission simulations continue with orbital and surface assets.

Lunar Terrain Vehicle (LTV)

Crew Landing Services

Pressurized Rover

Fission Surface Power

ISRU Pilot Plant

Surface Habitat

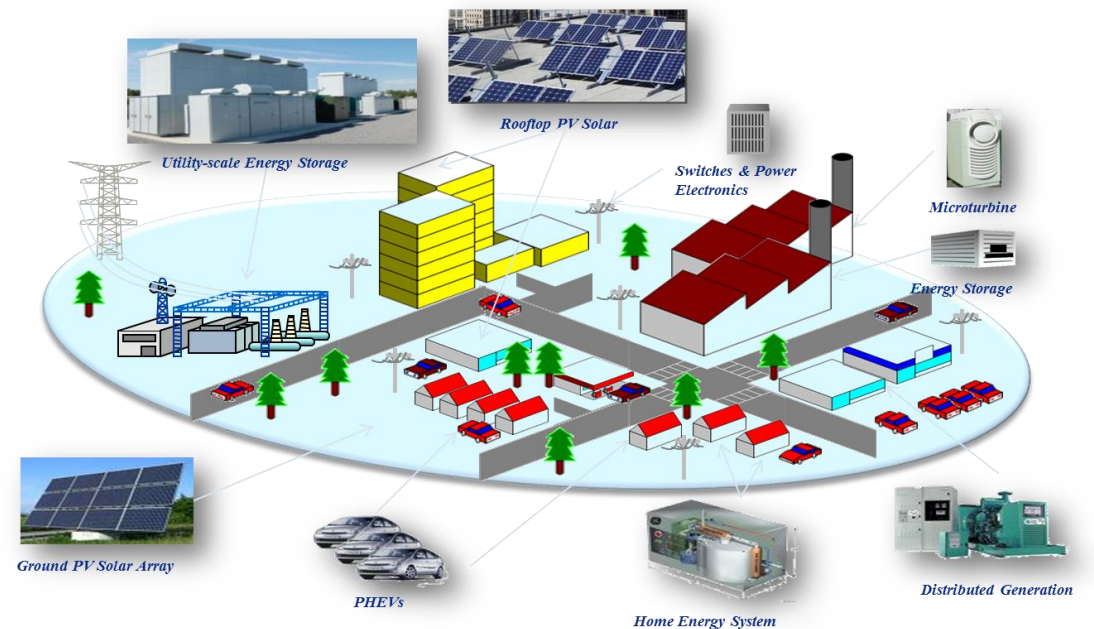
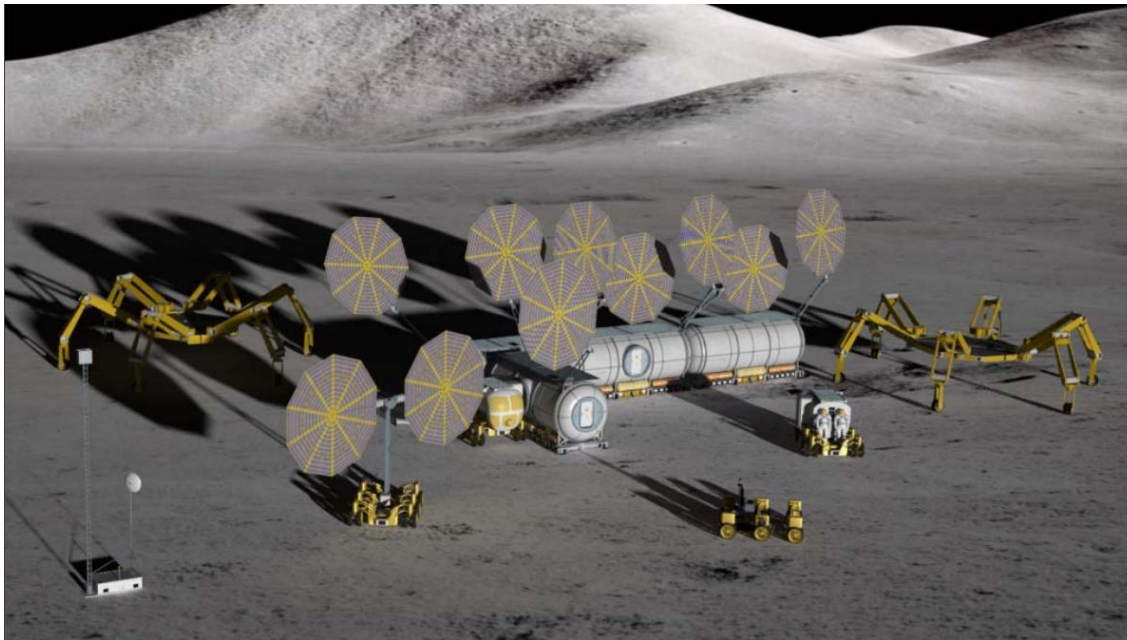
SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION

MULTIPLE SCIENCE AND CARGO PAYLOADS | U.S. GOVERNMENT, INDUSTRY, AND INTERNATIONAL PARTNERSHIP OPPORTUNITIES | TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS

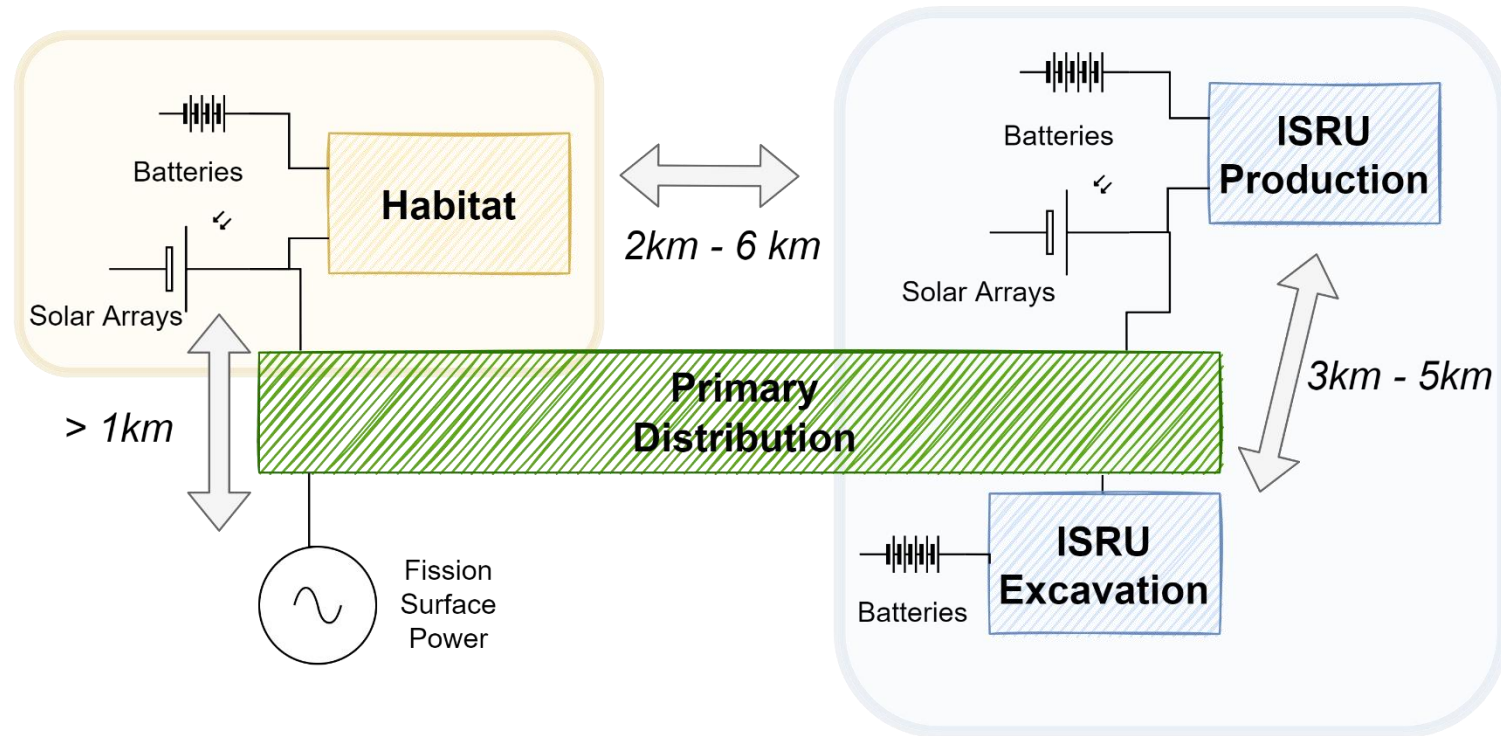
Case for a Lunar Power Grid



- **Meet needs for lunar surface operations**
 - Flexibility, evolvability, and reconfiguration
 - Optimal dispatch of power sources and energy storage to service loads & enhance reliability
 - Systematic integration of new sources and loads
 - Allow development and use of a common grid interface
 - **Allows for the deployment of future science loads that do not need to carry their own power generation**



Notional Artemis Base Camp Microgrid



- **Lunar surface south microgrid**

- Create local microgrids that can manage their own power
- Primary distribution system to enable power sharing between local microgrids
- Additional power sources (such as FSP) that can be utilized by and local microgrids
- Additional power loads can connect to primary power distribution system

Notional Artemis Base Camp Microgrid

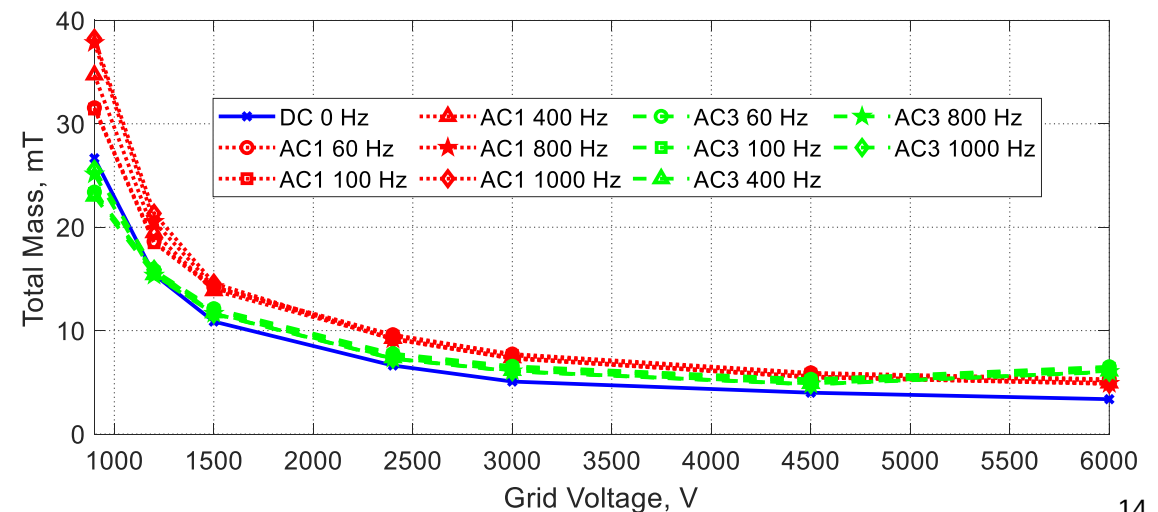
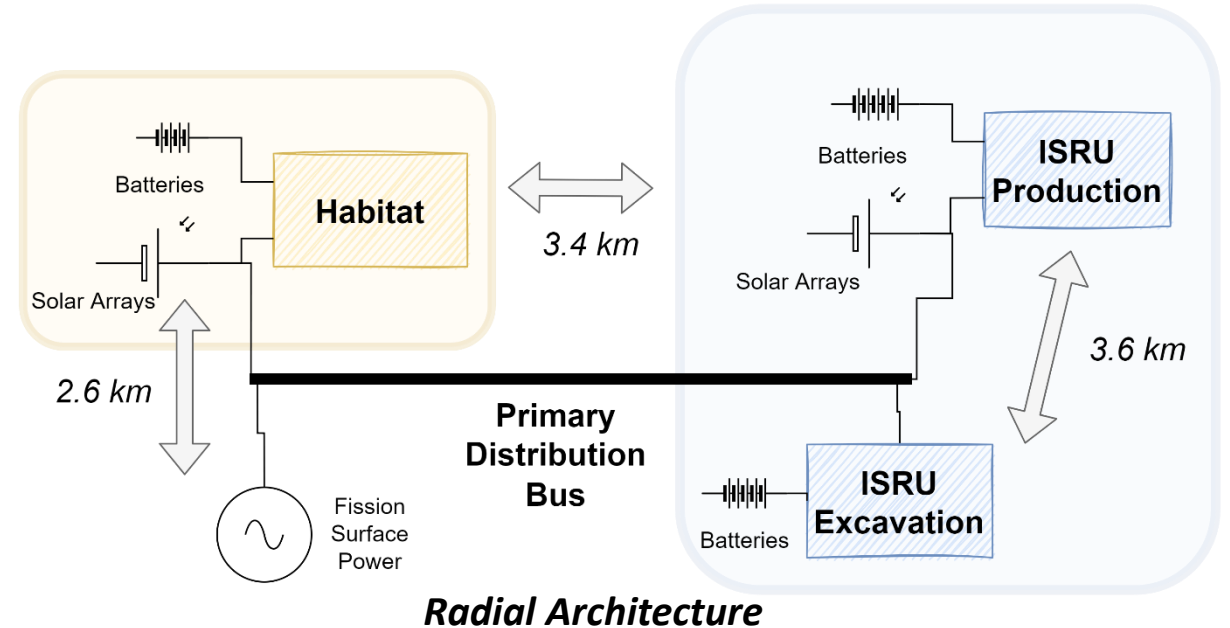


- Trade studies focused on primary power distribution system

- Architecture (radial, ring, mesh)
- Power type (AC vs DC)
- Voltage: (600 V – 6 kV)
- Data contains estimated mass of converters + cables

- Results

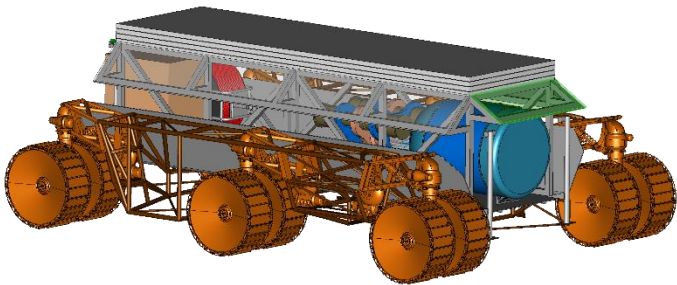
- Increasing voltage up to 3 kV has large mass advantages
 - Especially higher voltages
- AC vs DC at a single voltage is marginal
 - Max DC: 1.5 kV
 - Rad hard limitations
 - Max AC: none known



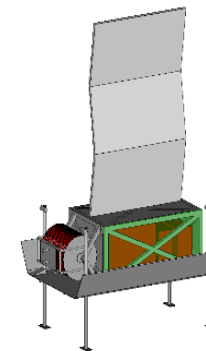
Fission Surface Power (FSP)



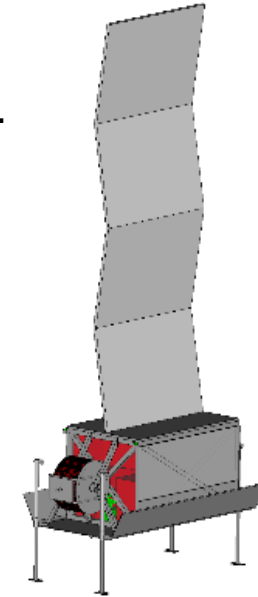
- **NASA and DOE are collaborating on the development of a 40 kWe fission surface power system for a demonstration on the moon by late 2020s with extensibility to Mars missions**
 - DOE has designated Idaho National Laboratory to manage development contracts. Los Alamos National Laboratory will provide subject matter expertise for reactor design
- **Develop the system for a 10-year life, support sustainable lunar operations**
- **Government reference design technical specs**
 - 10,000 kg mass estimate, 250-270 kg/kw
 - System is separated into 3 packages: power system, controllers, and load converter
 - Power conversion: Four - 6 kWe Stirling pairs, sodium heat pipes
 - 1-3 km power transmission to users. Elevated voltage (2 kV+) proposed. Assessing risks.
 - Nominal thermal power: 250 kWth
 - Heat transfer: sodium vapor heat pipe



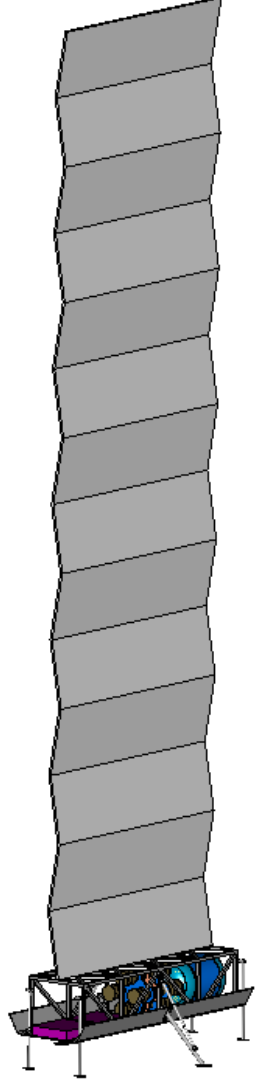
40 kW power system on lunar rover



User I/F



Control electronics



Power system

- 1) Oleson, Steven et al. "A Deployable 40 kWe Lunar Fission Surface Power Concept" Nuclear and Emerging Technologies for Space (NETS) 2022.
- 2) Barth, C. and Pike, D. "Lunar power Transmission for Fission surface power" Nuclear and Emerging Technologies for Space (NETS) 2022

Solar Array Development – Lunar Surface



- Vertical Solar Array Technology (VSAT) project led by STMD's Game Changing Development program and NASA Langley in collaboration with NASA Glenn
- Autonomous deployment systems of 30 ft masts, stable on steep terrain, resistant to abrasive lunar dust and minimized both mass and packaged volume for ease in delivery to the lunar surface

Base period contracts, valued at up to \$700,000 each, awarded as 12- month fixed price contracts to:

- Astrobotic Technology, Pittsburgh, PA
- ATK Space Systems (Northrop Grumman), Goleta, CA
- Honeybee Robotics, Brooklyn, NY
- Lockheed Martin, Littleton, CO
- Space Systems Loral (Maxar Technologies), Palo Alto, CA

The companies will provide system designs, analysis, and data.

The agency plans to down select up to two companies and provide additional funding, up to \$7.5 million each, to build prototypes and perform environmental testing, with the ultimate goal of deploying one of the systems on the Moon's South Pole near the end of this decade.

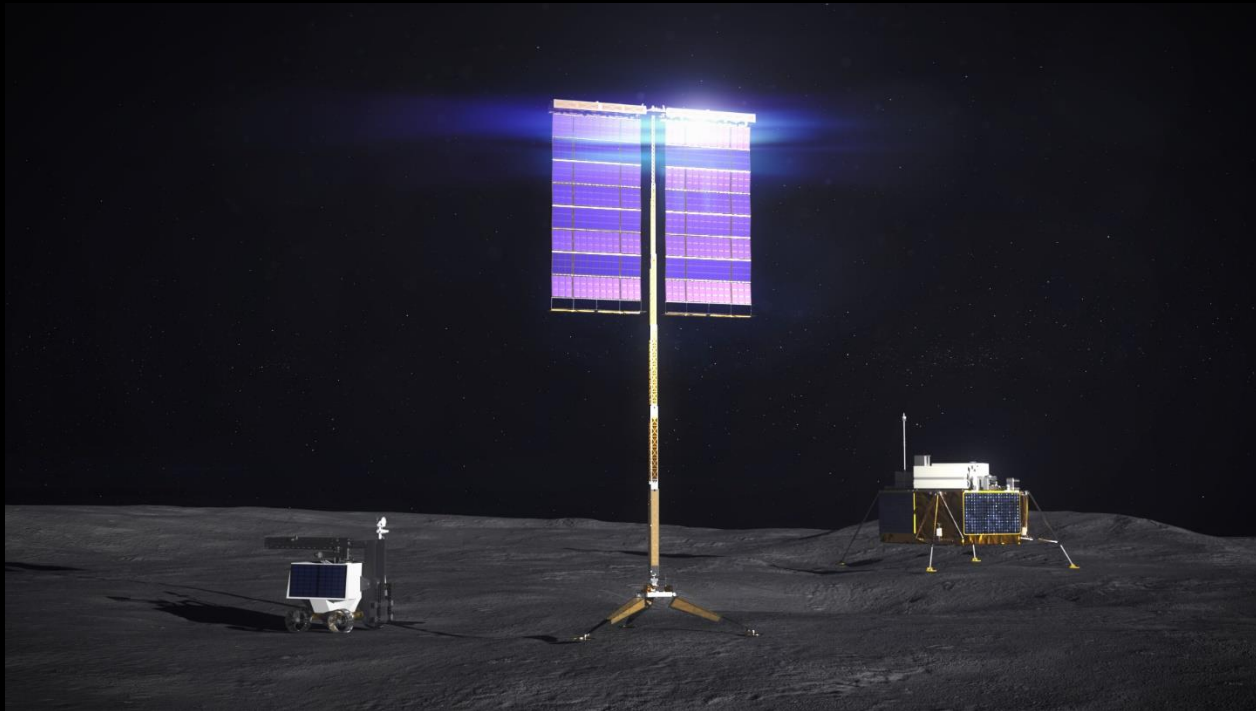


Photo credit: NASA

Microgrid Definition and Interface Converter for Planetary Surfaces (MIPS)

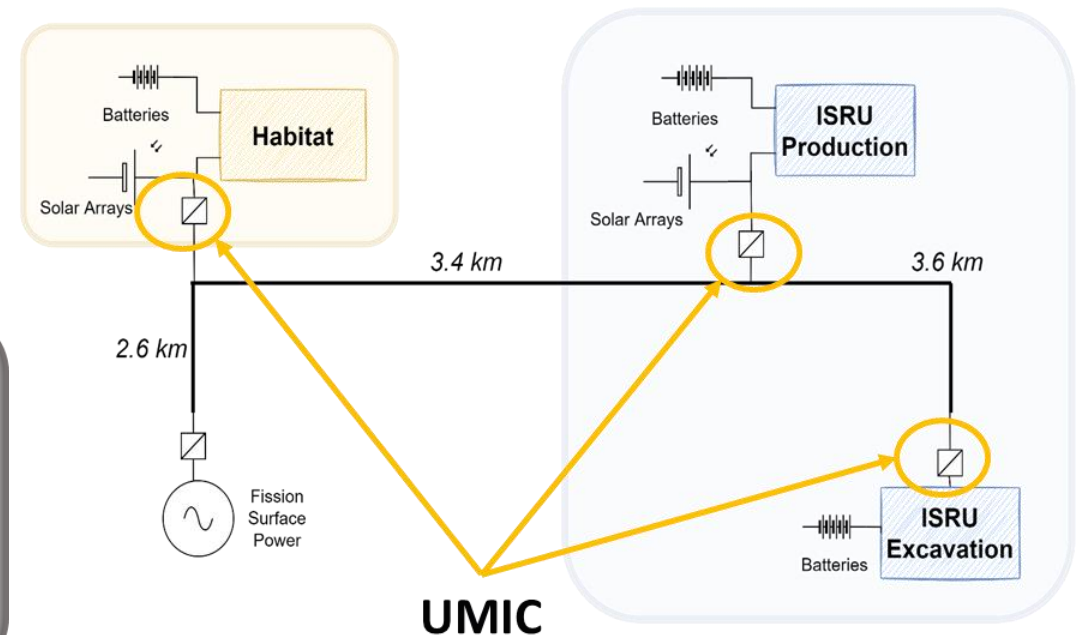
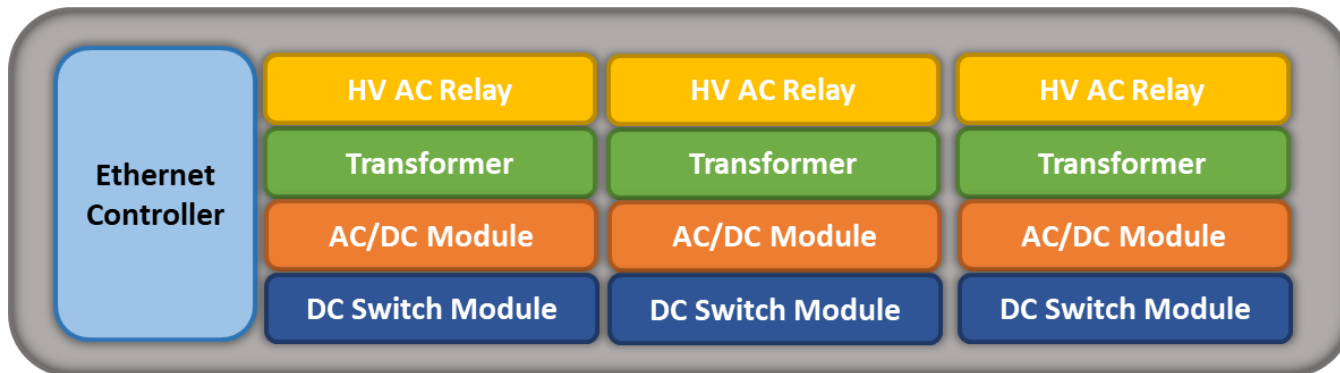


- **Universal Modular Interface Converter (UMIC)**

- Power converter that provides bidirectional power flow between high voltage power transmission and standard 120 VDC space power distribution system
- Able to transmit 10s of KW of power over km distance, enabling power sharing, highly available/reliable power for new users

- **Prototype development will focus on:**

- Developing standard interfaces and specifications:
 - Vendor agnostic; grid-tie regulations
- Determining control strategies (local and grid)
- Characterizing performance (limits, efficiency, etc.)



Advanced Modular Power Systems (AMPS)

Autonomous Power Control



Why is this project important?

- *Future NASA missions require advancements in electrical power system technology that will provide unprecedented levels of resilience, reliability, and autonomy.*
- *Solves the very real and practical problems of power management during mission critical environments beyond low-earth orbit (LEO), such as the lunar surface*

Objectives

- Increase the resilience, reliability, and autonomy of an electric power system using a hierarchical, multi-layer control structure
 - Services include voltage regulation, power sharing, fault tolerance, reconfiguration, interoperability, etc.

Current Activities

- **Collaboration with Sandia National Laboratories for *robust, autonomous, and fault-tolerant DC microgrids* to enable sustainable lunar surface power.**
- **Implementation and evaluation of the US Army developed Tactical Microgrid Standard for space power systems.**

Lunar Surface Habitat

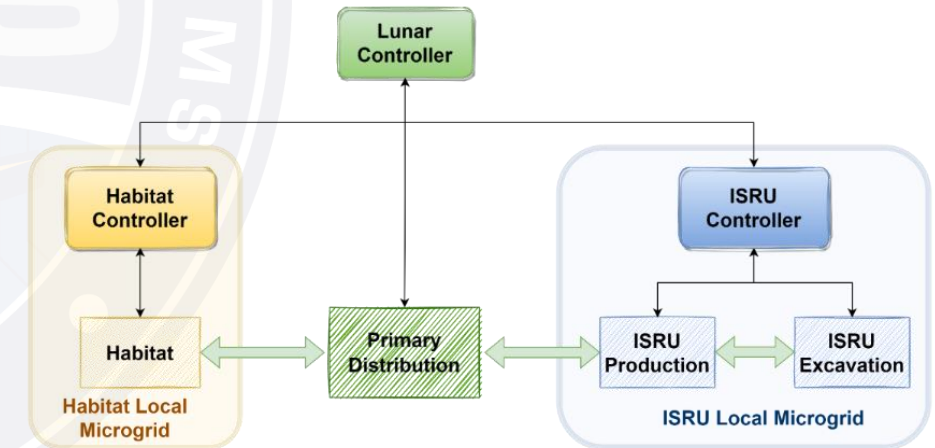


Demonstrate technology required for Mars Missions

Mars Surface Habitat



Communication latency time drives autonomous power needs

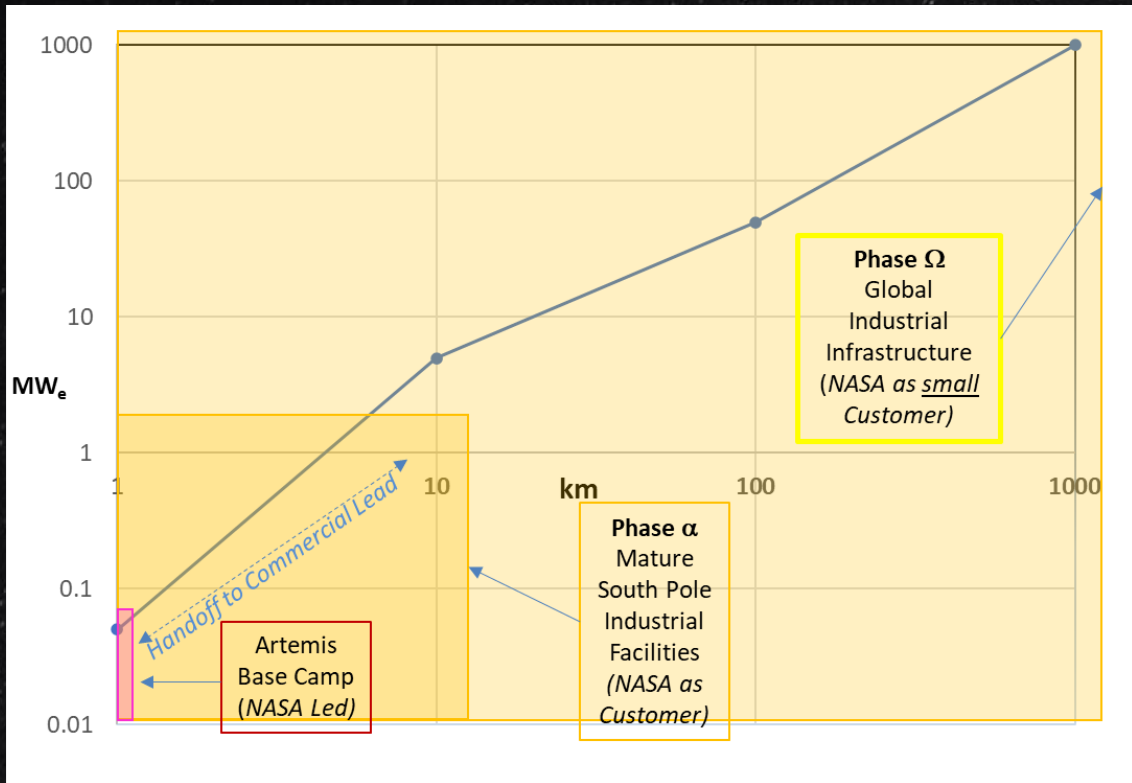


Hierarchical control architecture

Beyond Artemis



Envisioned Growth of Lunar Presence



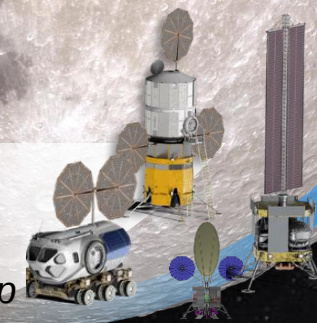
Ultimate Global Infrastructure – Phase Ω (2040+)

Additional technology gaps to be closed to enable building blocks for global infrastructure



Mature South Pole Industrial Facilities – Phase α (2030+)

Current and high priority new technology projects support gap closure for industrial-scale Polar infrastructure building blocks beyond Artemis Base Camp

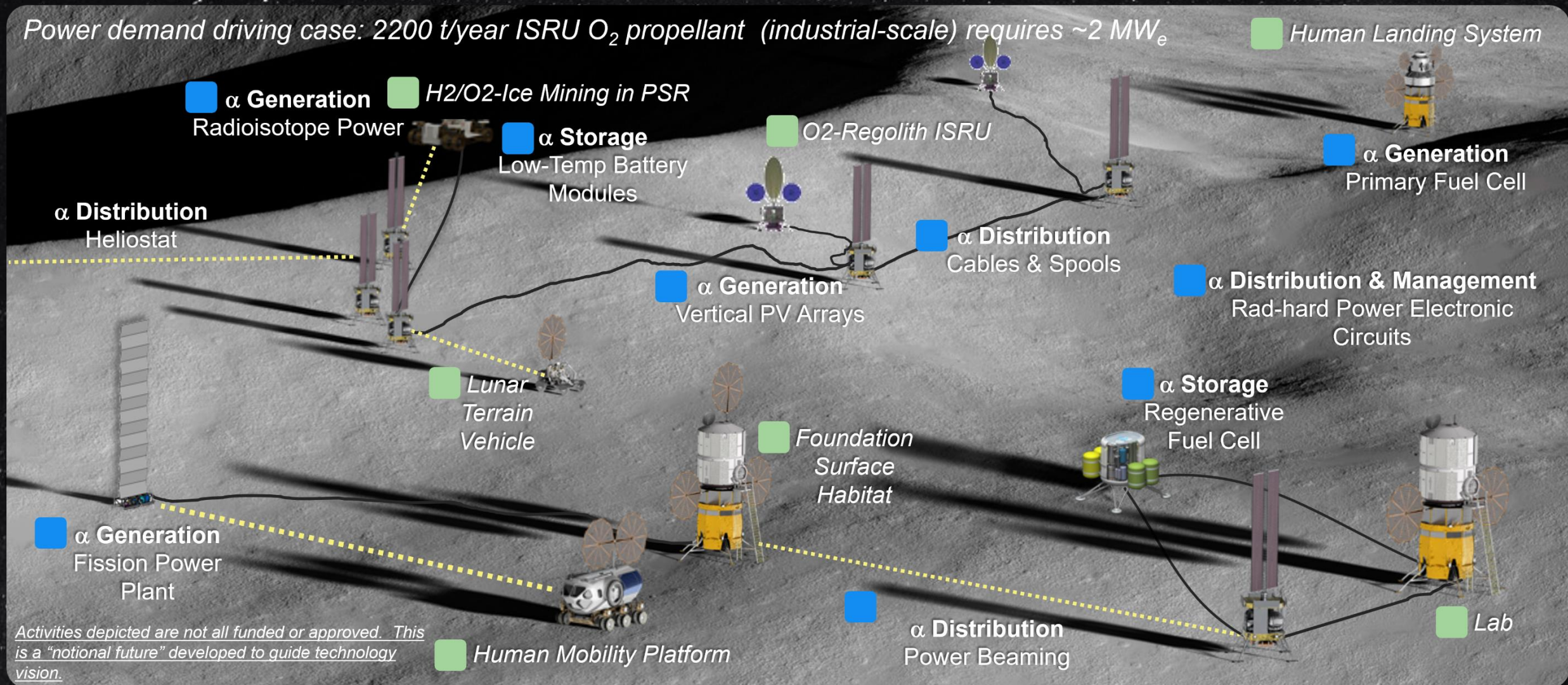


Power Architecture Building Block



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

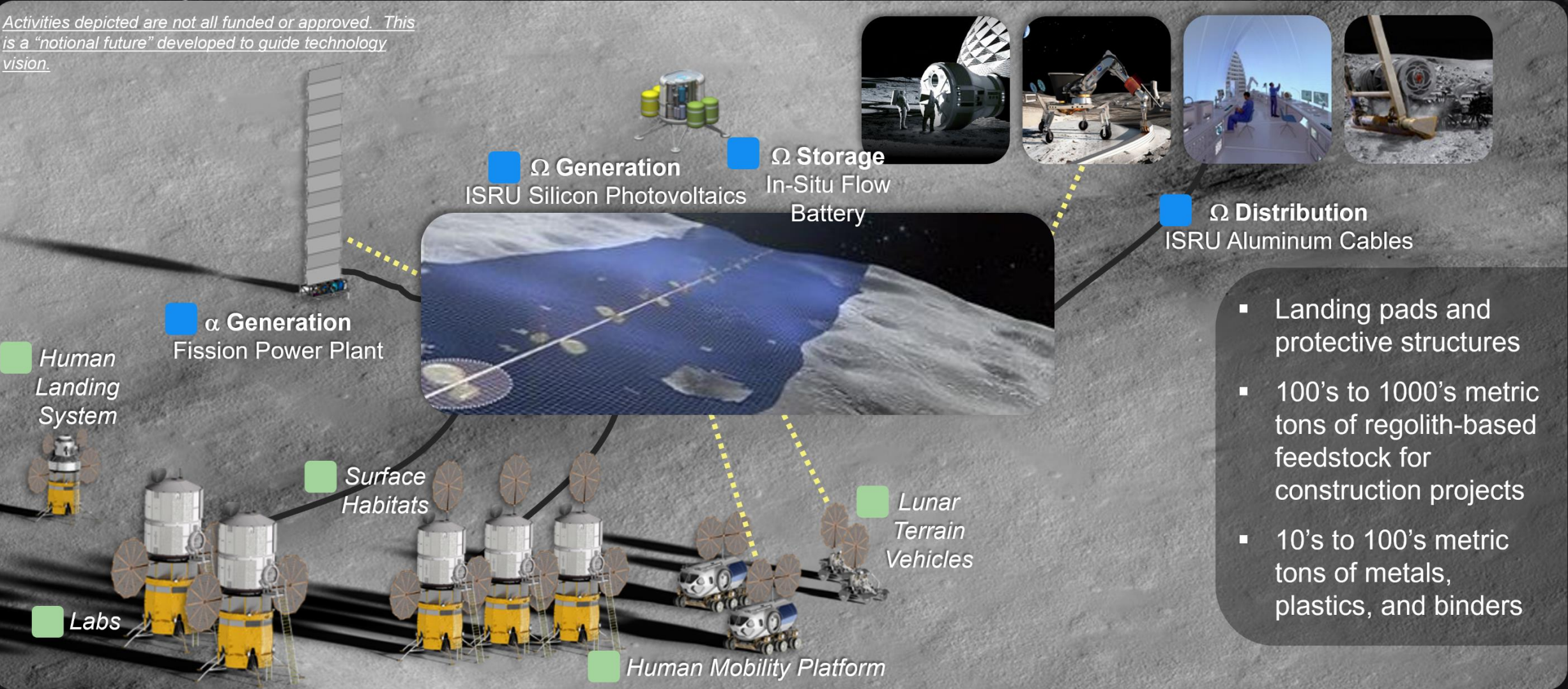
Power demand driving case: 2200 t/year ISRU O₂ propellant (industrial-scale) requires ~2 MW_e



Power Architecture Building Block

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

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





ARTEMIS SURFACE TECHNOLOGY OBJECTIVES

The Lunar Surface Innovative Initiative works across industry, academia and government through in-house efforts and public-private partnerships to develop transformative capabilities for lunar surface exploration.

- **In-situ resource utilization** technologies for collecting, processing, storing, and using material found or manufactured on the Moon or other planetary bodies
- **Surface power technologies** that provide the capability for sustainable, continuous power throughout the lunar day and night
- **Dust mitigation technologies** that diminish dust hazards on lunar surface systems such as cameras, solar panels, space suits, and instrumentation
- **Extreme environment technologies** that enable systems to operate throughout the range of lunar surface temperatures
- **Extreme access technologies** that enable humans or robots to efficiently access, navigate, and explore previously inaccessible lunar surface or subsurface areas
- **Excavation and construction technologies** that enable affordable, autonomous manufacturing or construction





- **Strategic partnerships with industry and academia**
 - Small Business Innovation Research (SBIR) / Small Business Technology Transfer (STTR)
 - STMD Announcement of Collaboration Opportunity (ACO)
 - NASA Tipping Point (TP)
 - Space Technology Research Institutes (STRI) Grants
 - NASA Space Technology Graduate Research Opportunities (NSTGRO)
 - Lunar Surface Technology Research (LuSTR Opportunities)
 - Early Career Faculty (ECF)
- **More information regarding NASA Programs**
 - STMD Solicitations and Opportunities:
 - <https://www.nasa.gov/directorates/spacetech/solicitations>
 - NASA Research Opportunities
 - <https://nspires.nasaprs.com/external/>

Thank you

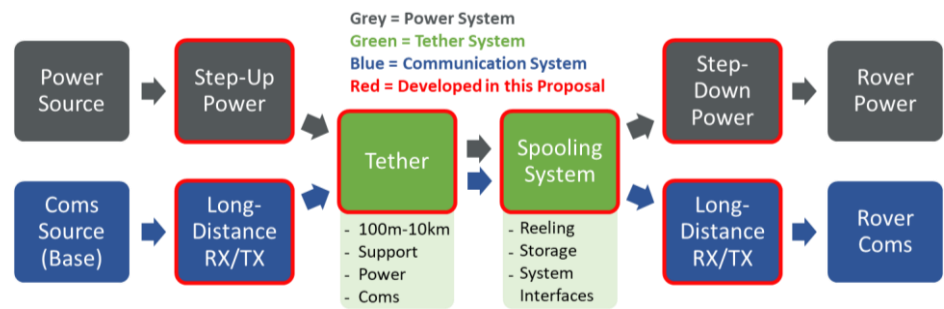


Tethered Power Systems for Lunar Mobility and Power Transmission



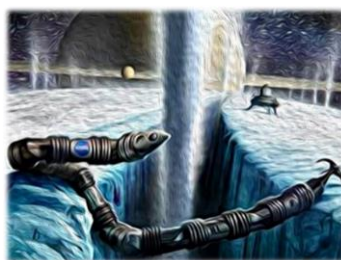
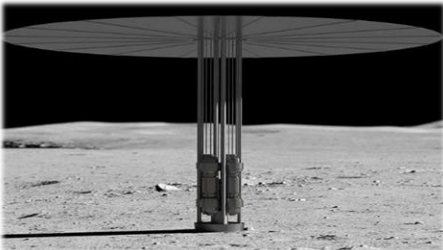
Our objective is to develop a tether-based power transmission system to provide power over several kilometers to serve remote loads. The end-to-end tether power system will deliver 100 W – 10 kW of power at above 90 % efficiency and provide communications to:

- Enable high-power transmission capabilities for nuclear or solar power systems
- Enable rover access to extreme terrain, like lunar craters, pits, caves, and lava tubes



Applications for the TYMPO system include a number of end-users for the lunar surface and other planetary bodies throughout the solar system, such as Mars and Enceladus. Some specific end users include:

- Fission Surface Power and Surface Solar Power • 1 km • 10 kW • Fiber comms
- Moon Diver (Tethered Lunar Pit Descender) • 300 m • 100 W • Copper comms
- EELS (Enceladus Vent Crawler) • 3 km • 200 W • Fiber Comms
- PRIME (Europa Melt Probe) • 50 m • 200 W • Fiber coms
- FARSIDE (tethered telescope array for the Moon) • 12 km, 70 W, Fiber coms



Key Performance Parameter	State-of-the –Art (SOA)	Threshold Value	Goal Value
Step-Up Converter Efficiency	90 %	92.5 %	97 %
Step-Down Converter Efficiency	N/A	92.5 %	97 %
Converter Power Density	0.3 W/cm ³	1 W/cm ³	2 W/cm ³
Converter Specific Power	250 W/kg	500 W/kg	1 kW/kg
End-to-End Efficiency	N/A	80 %	90 %
Tether Communications	N/A	4 mbits @ 10 km	8 mbits @ 10 km

Develop a stand-alone tether power subsystem that can be integrated into landers, rovers, and power transmission systems for numerous lunar applications. The system elements below will be developed and raised to TRL 6 over 3 years:

- GaN-Based Modular multilevel converter (MMC) DC-DC converter modules for step up and step down conversion at 1 kW+, 95% efficient from 100 V to 1.5 kV
- A high voltage (500 V - 1.5 kV) tether capable of 100 m – 10 km
- Dual communications system supporting both fiber optic and data over power lines uplink (8 kbps) and downlink (8 mbps) communications for various mission types

