NASA Lunar Surface Operations & Power Grid

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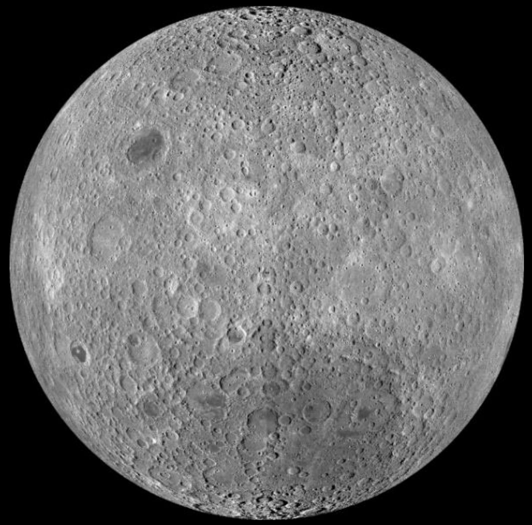
NASA Artemis Program

- **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 1 (2022) : uncrewed test of SLS and Orion
    - *Artemis 2: first crewed test flight of SLS and Orion*
    - *Artemis 3: first crewed lunar landing*
    - *Artemis 4: second crewed lunar landing*
    - *Artemis 5 – 8: TBD*

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

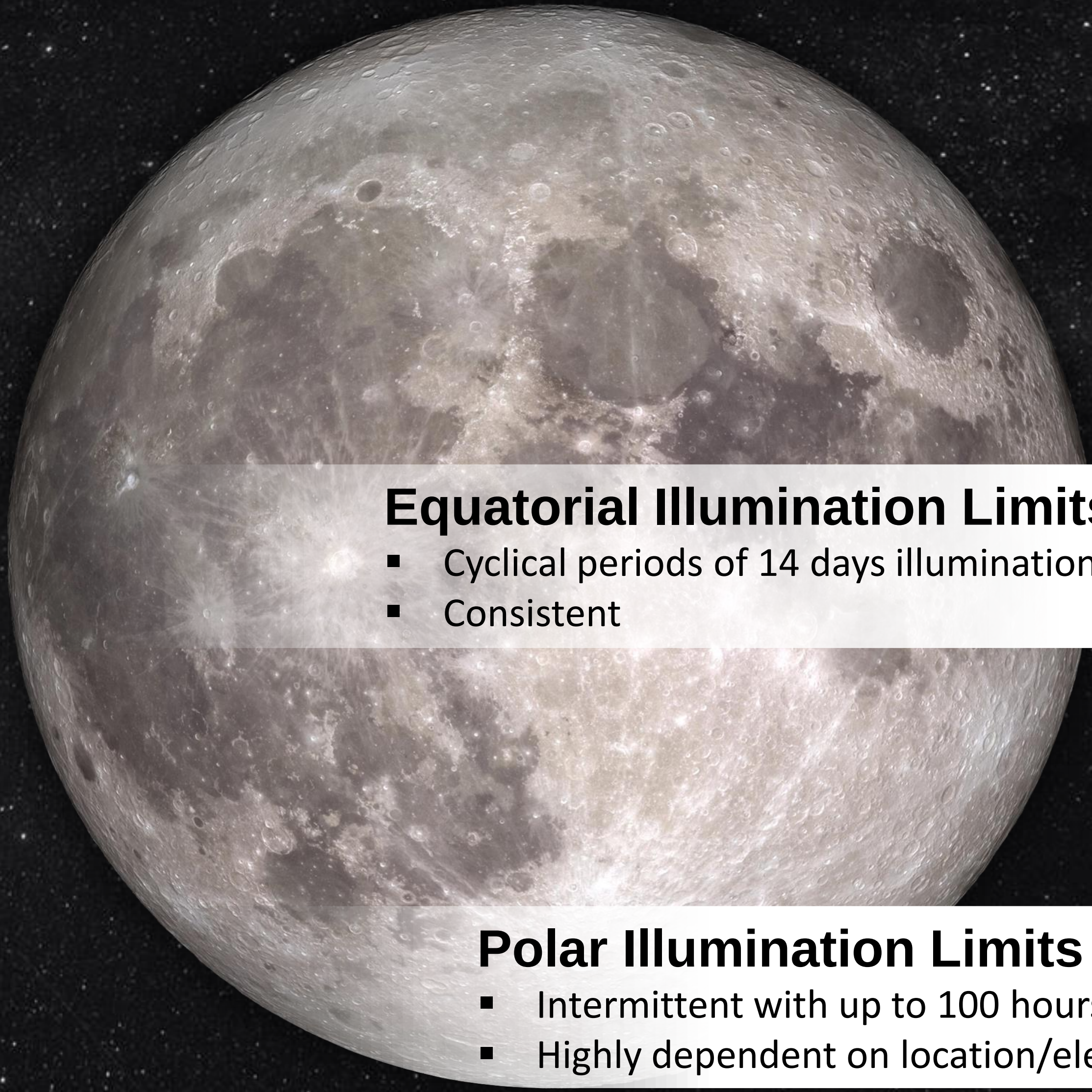
Near Side



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

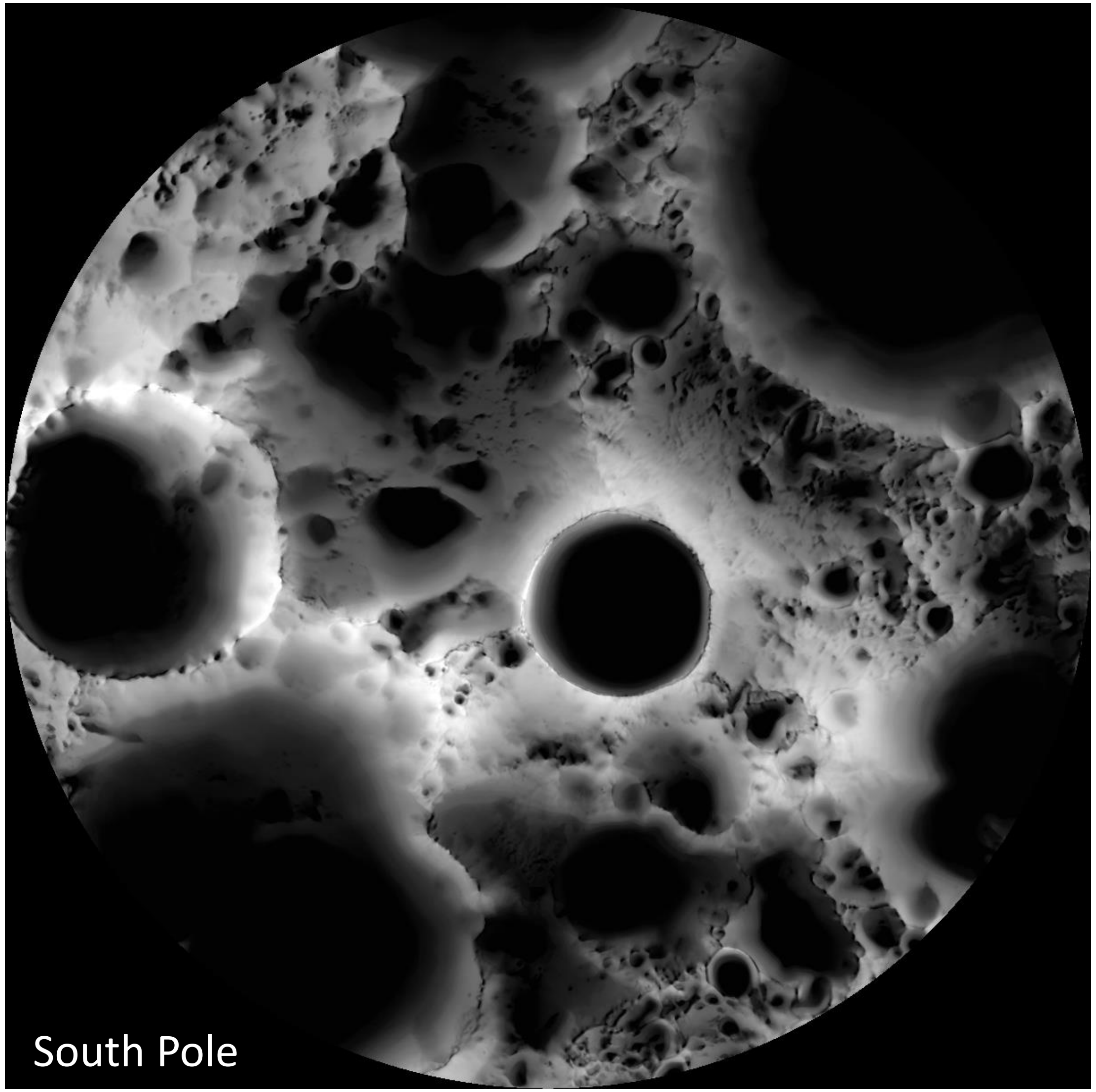
- Intermittent with up to 100 hours darkness
- Highly dependent on location/elevation

Chart provided JSC/John Scott
STMD Principal Technologist for Power And Energy Conversion

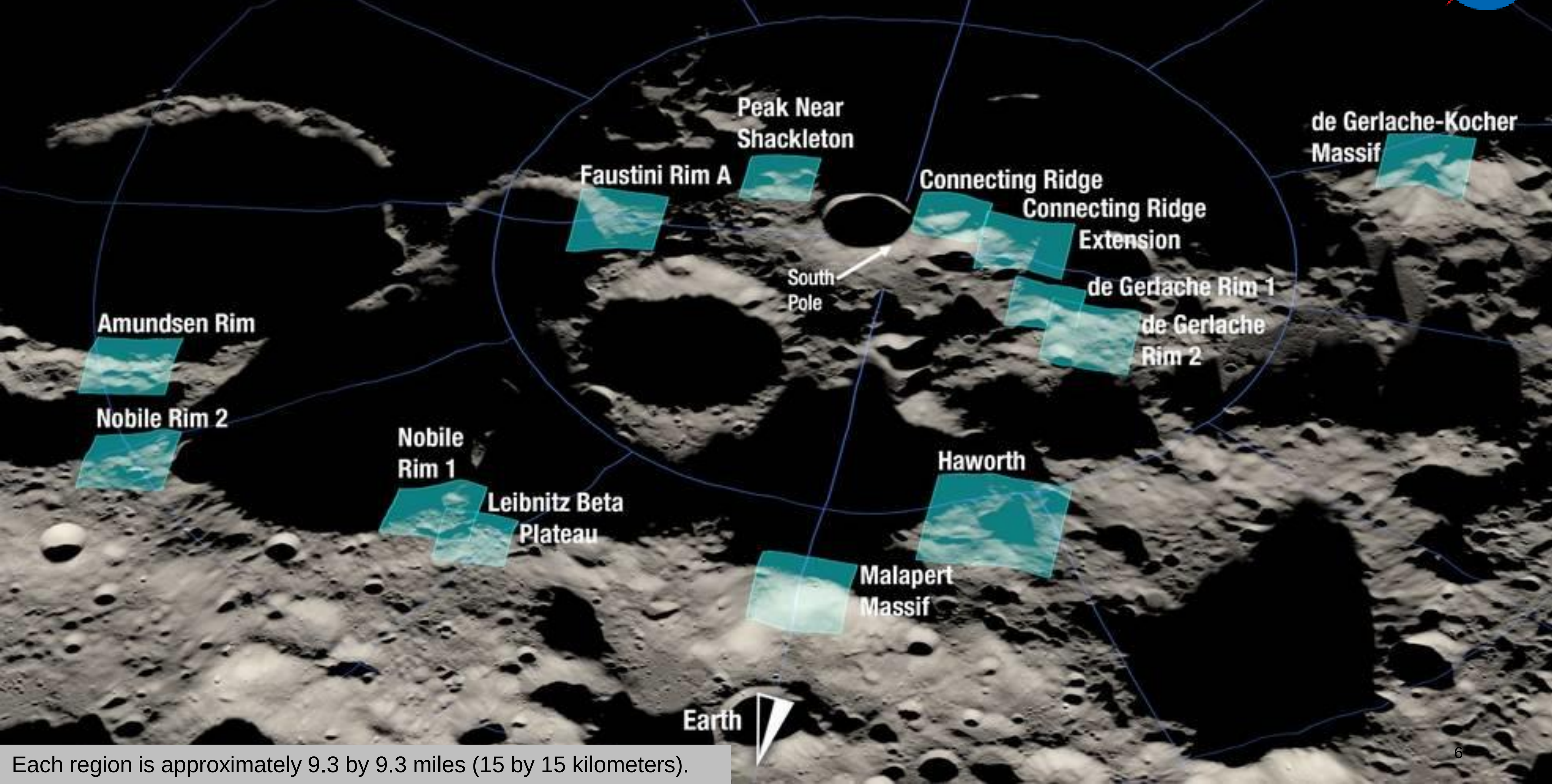
Polar Landing Sites - Criteria

- **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 ºC
    - Temperature never exceeds -173 ºC
    - Any water vapor that arrived at the lunar surface from comets or meteorites would have been trapped



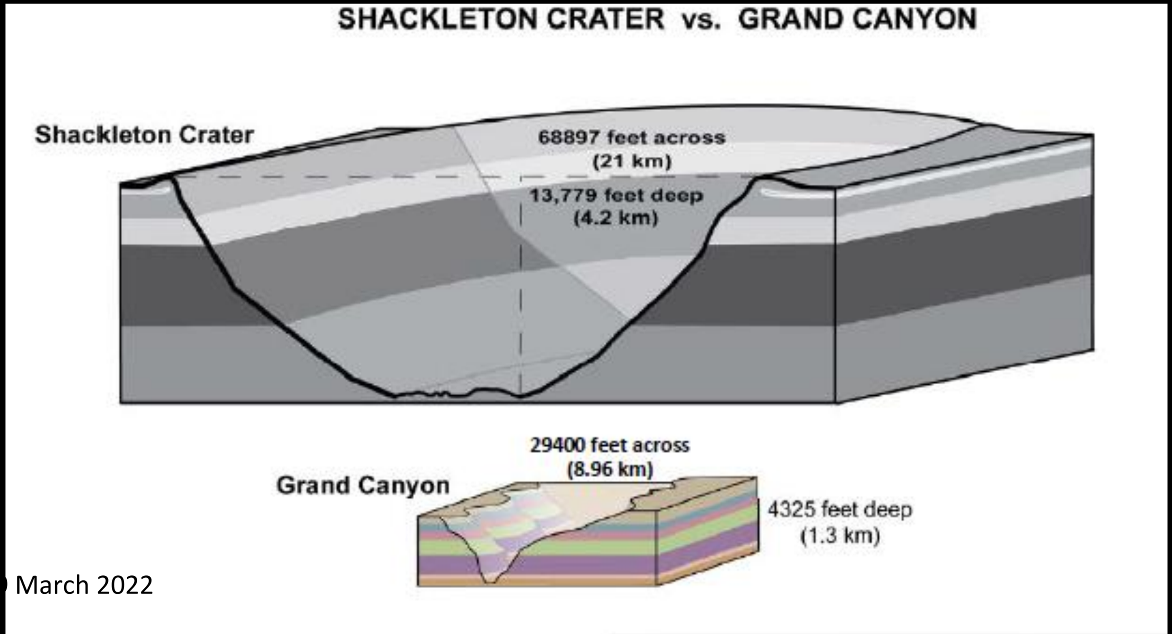
NASA Candidate Locations

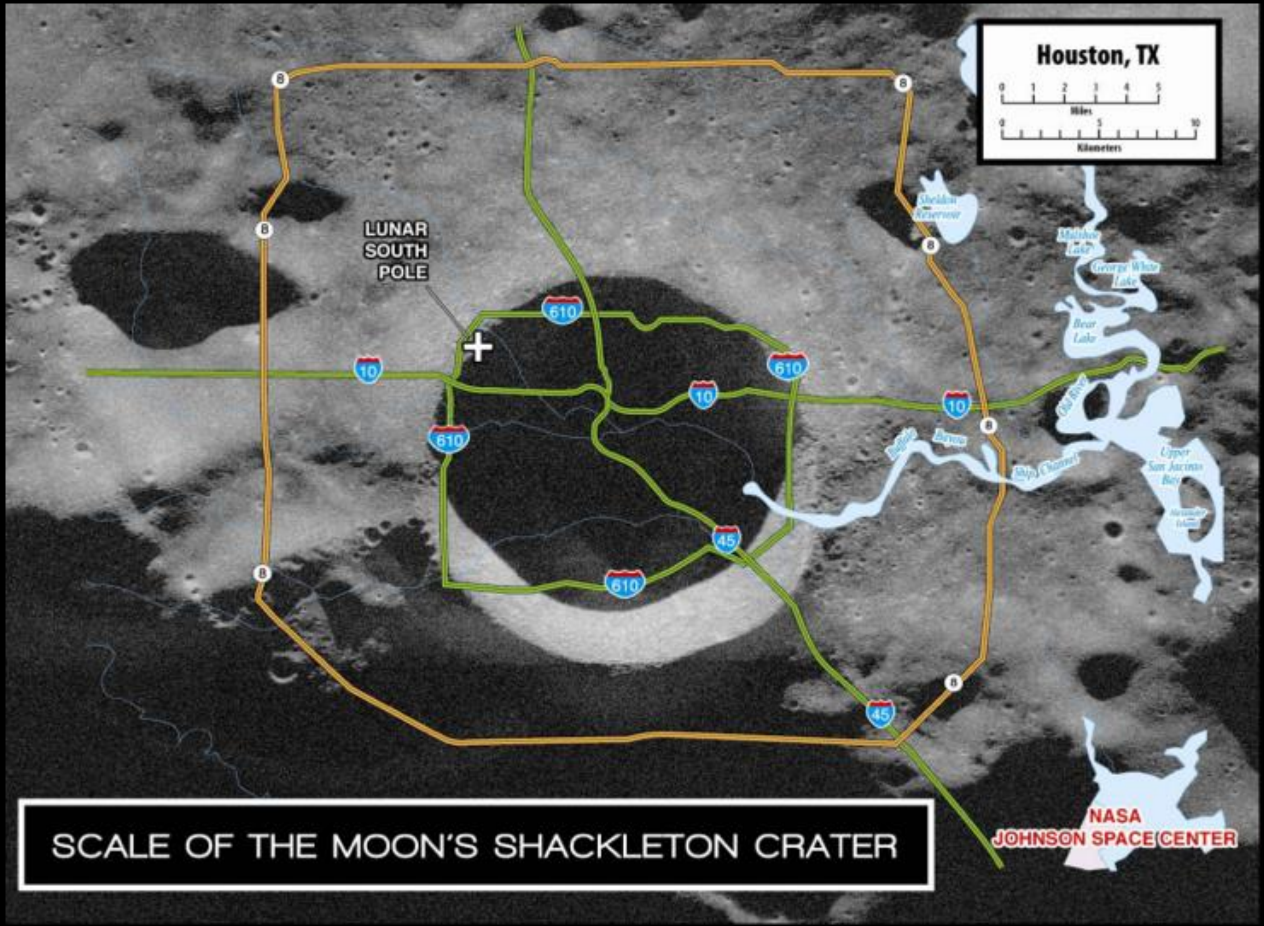


Each region is approximately 9.3 by 9.3 miles (15 by 15 kilometers).

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





Artemis Base Camp Zone

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.

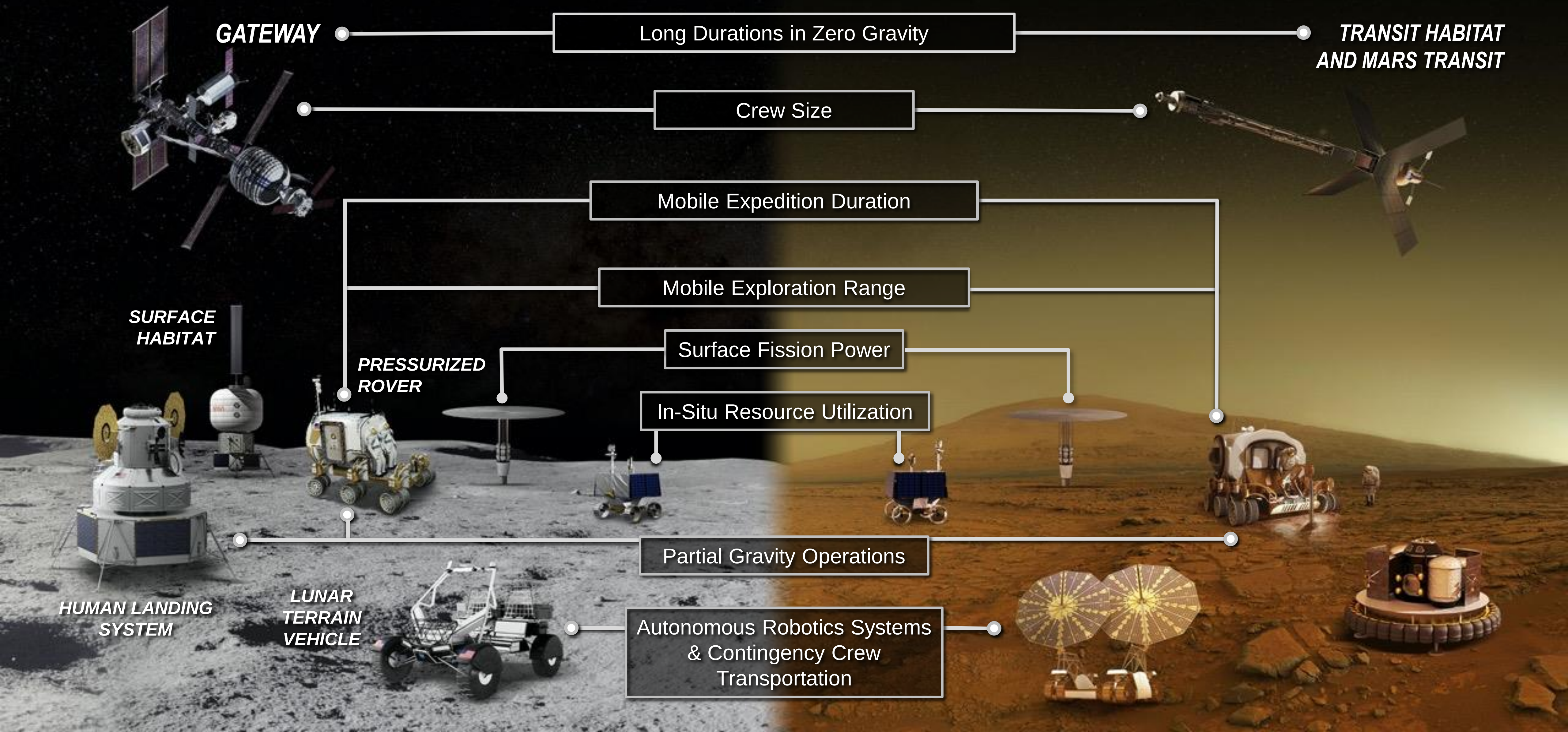
- **LI-1L:** Develop an incremental lunar power generation and distribution system that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels.

Mars Infrastructure (MI) Goal: Create essential infrastructure to support initial human Mars exploration campaign.

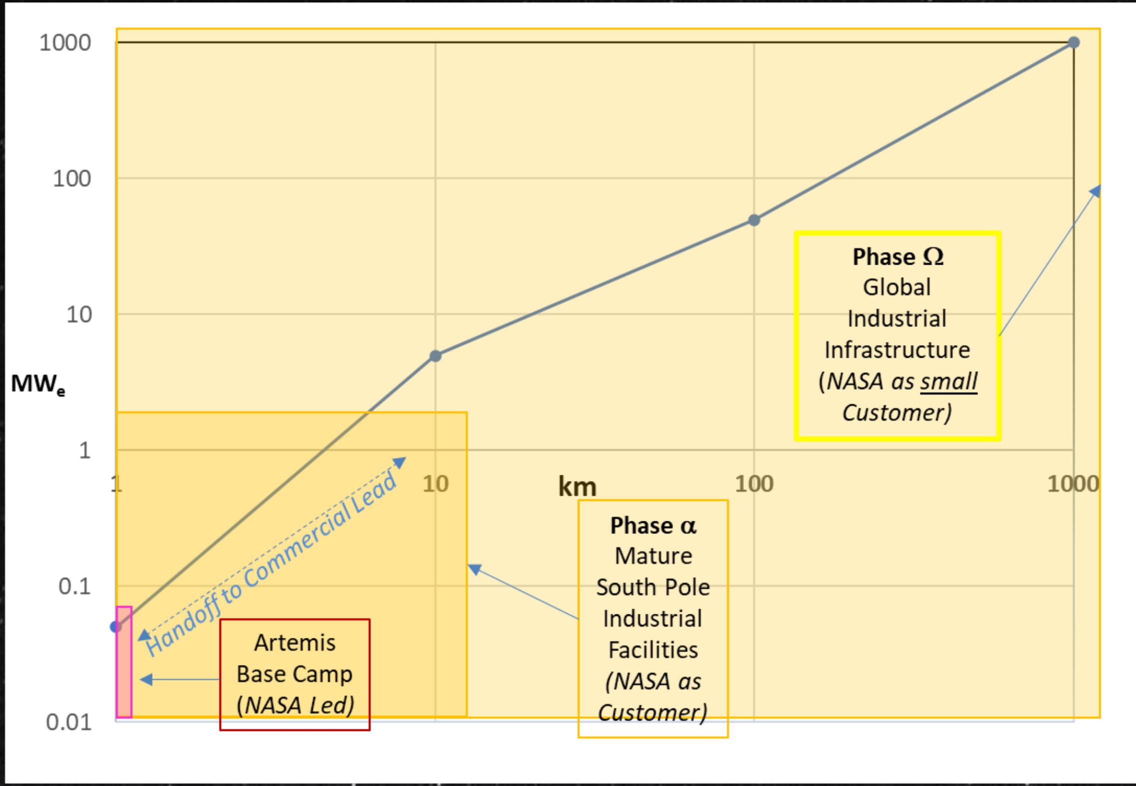
- **MI-1M:** Develop Mars surface power sufficient for an initial human Mars exploration campaign.

Moon to Mars Exploration

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

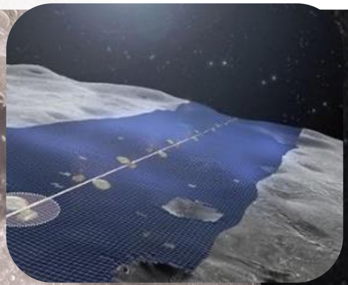


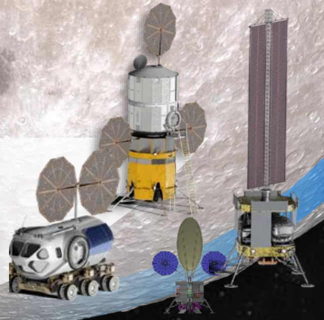
Envisioned Growth of Lunar Presence



Ultimate Global Infrastructure – *Phase Ω (2040+)*

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



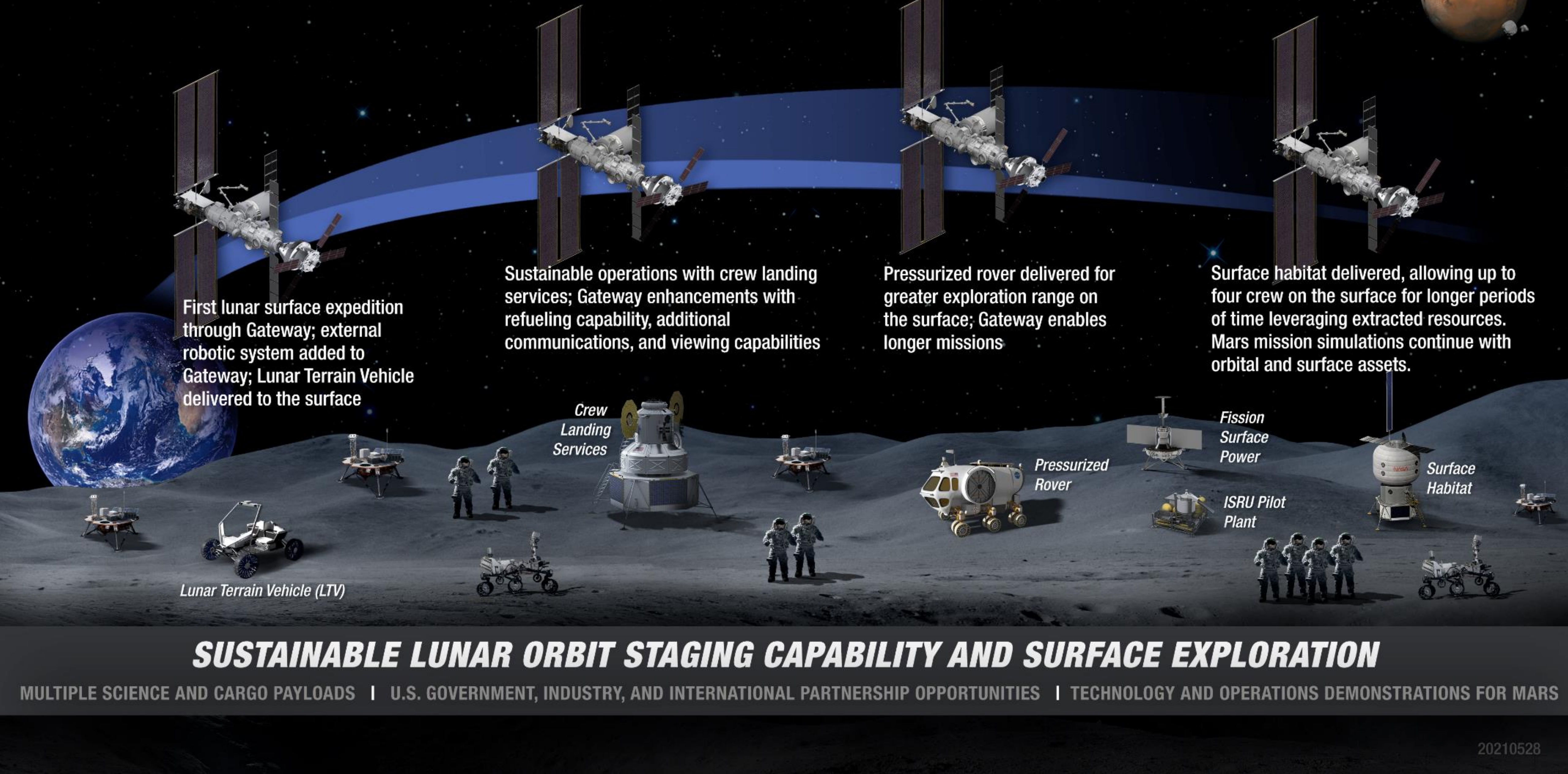


Mature South Pole Industrial Facilities – *Phase α (2030+)*

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

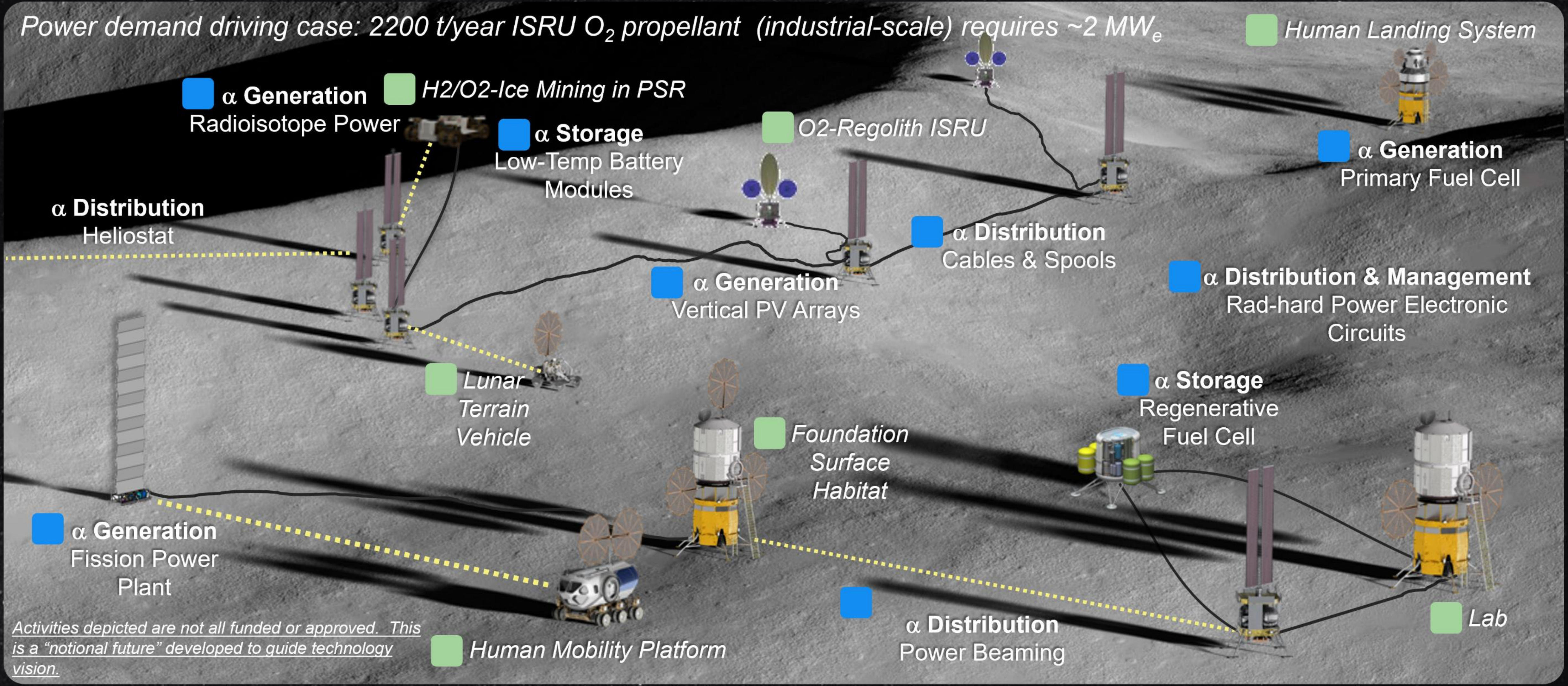
Chart provided JSC/John Scott
STMD Principal Technologist for Power And Energy Conversion

Artemis Base Camp Buildup



Power Architecture Building Block

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



Power system

Load

Chart provided JSC/John Scott

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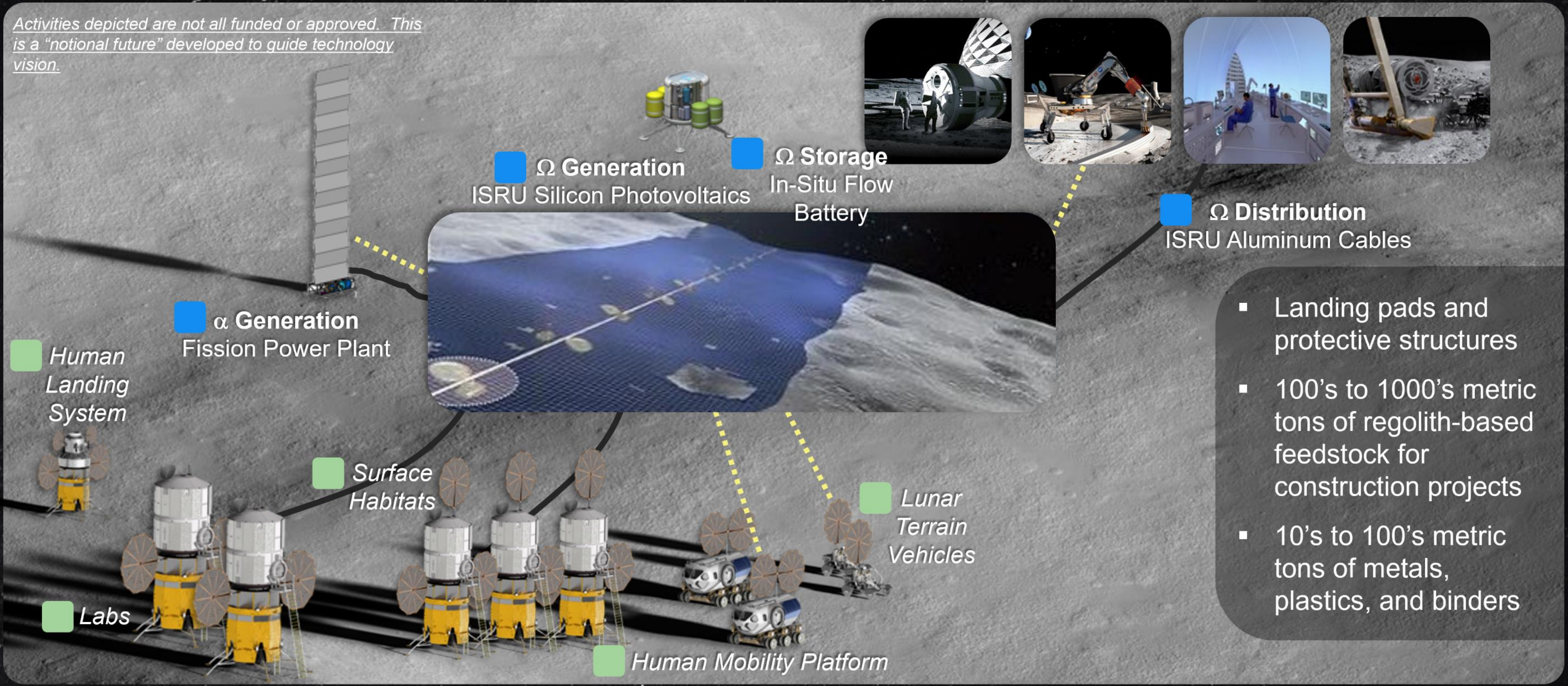
Power Architecture Building Block

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

Power system

Load

Chart provided JSC/John Scott
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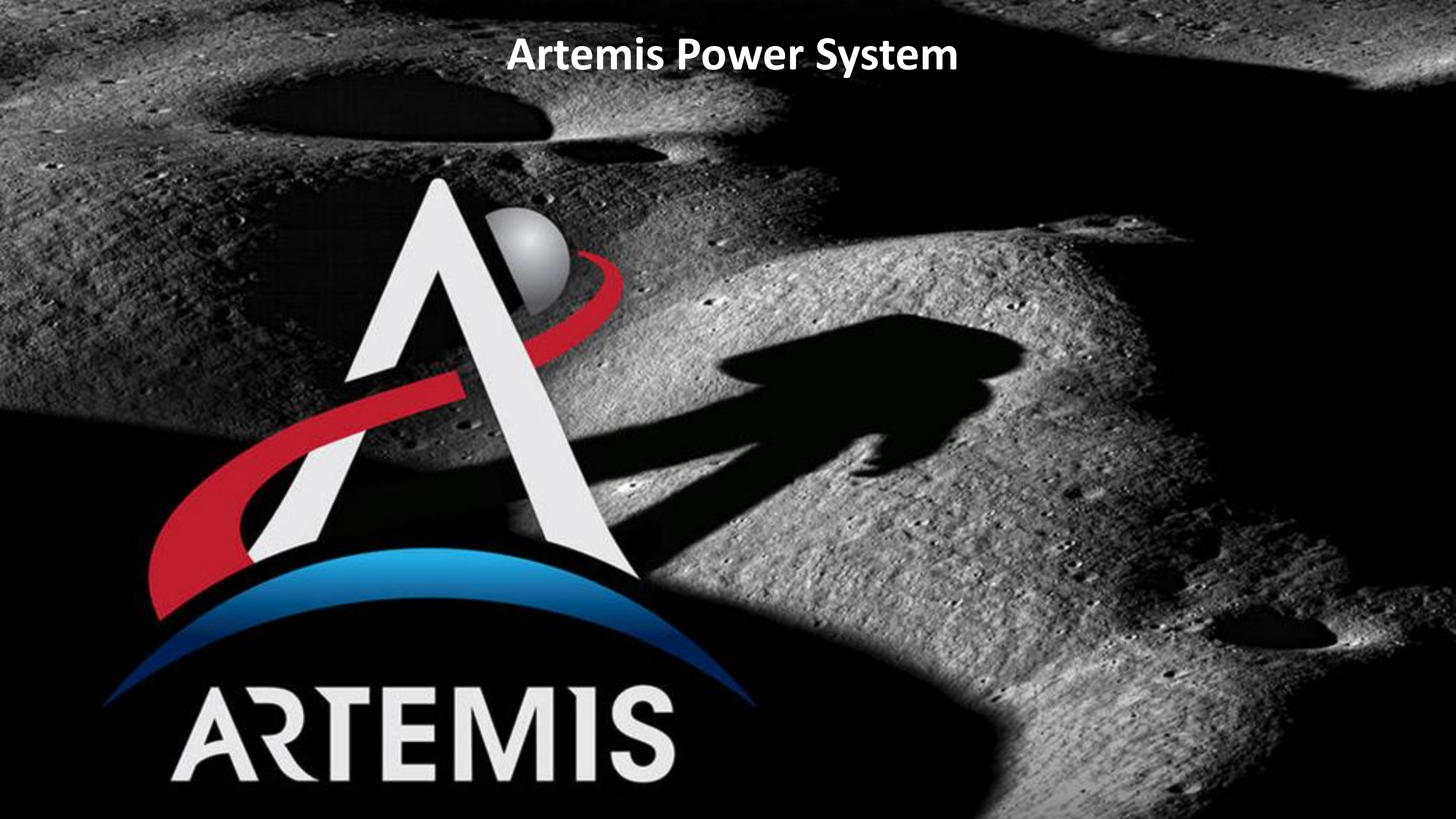
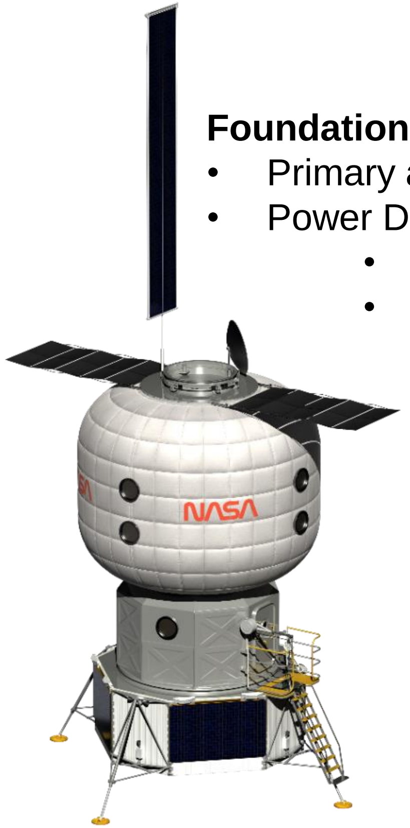
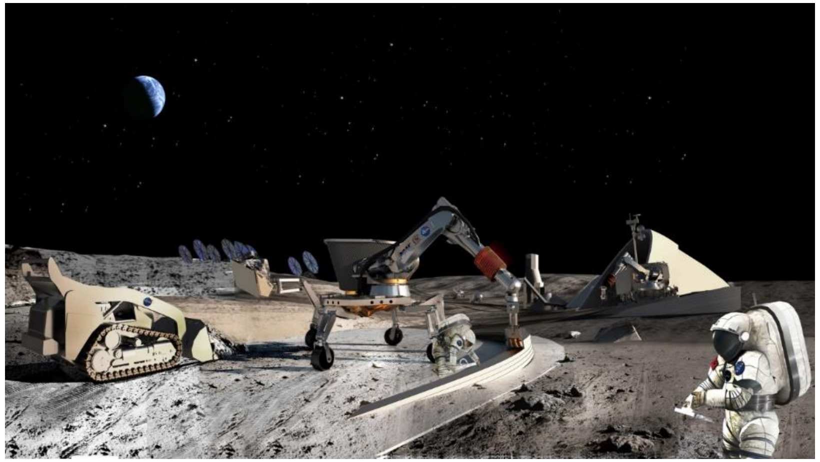
Artemis Power System



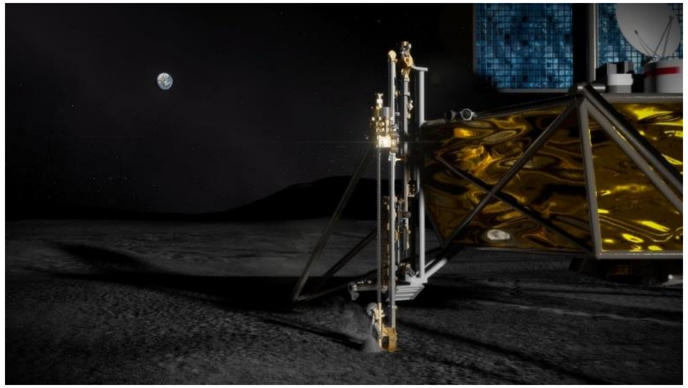
Artemis Lunar Surface Power Users



Foundation Surface Habitat
- Primary asset to achieve a sustained lunar presence
- Power Demand: ~20kW (crewed) / ~2kW (un-crewed)
  - 2-4 crew, 30-60 day capable habitat
  - Medical, exercise, galley, crew quarters, stowage



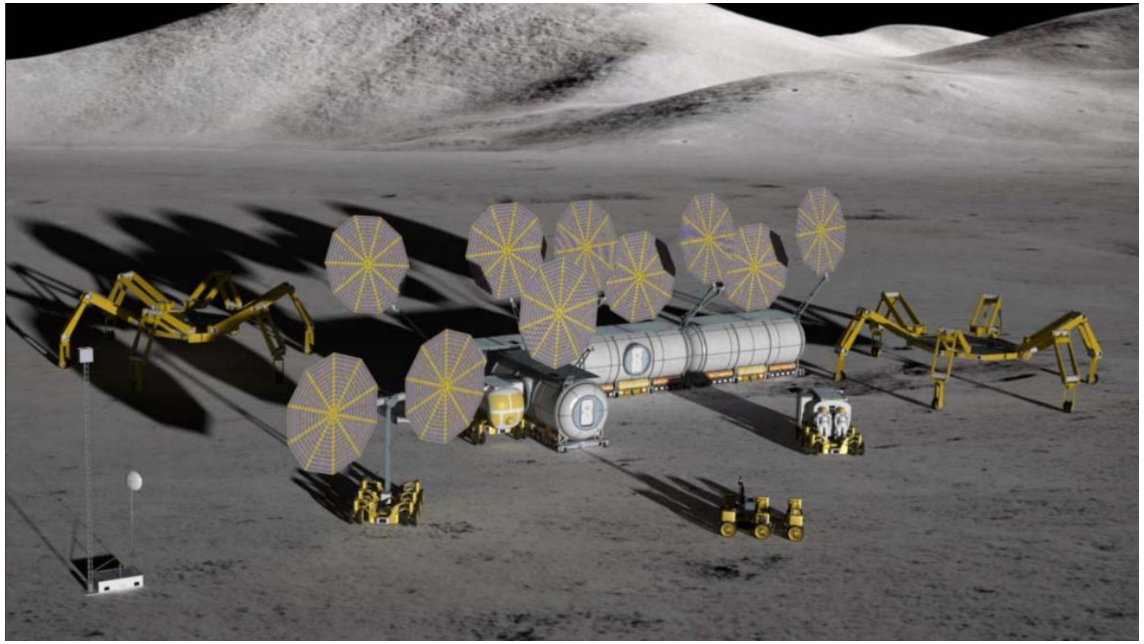
In-Situ Resource Utilization (ISRU)
- Largest power user: 60+ kW
  - Ridge: ~46 kW / Inside PSR crater: ~22 kW
- Restricted to operate during periods of heavy insolation
- Power is needed over long distances (3- 5km)
  - Mine water ice in crater, transport to crater rim, process into H_2, O_2

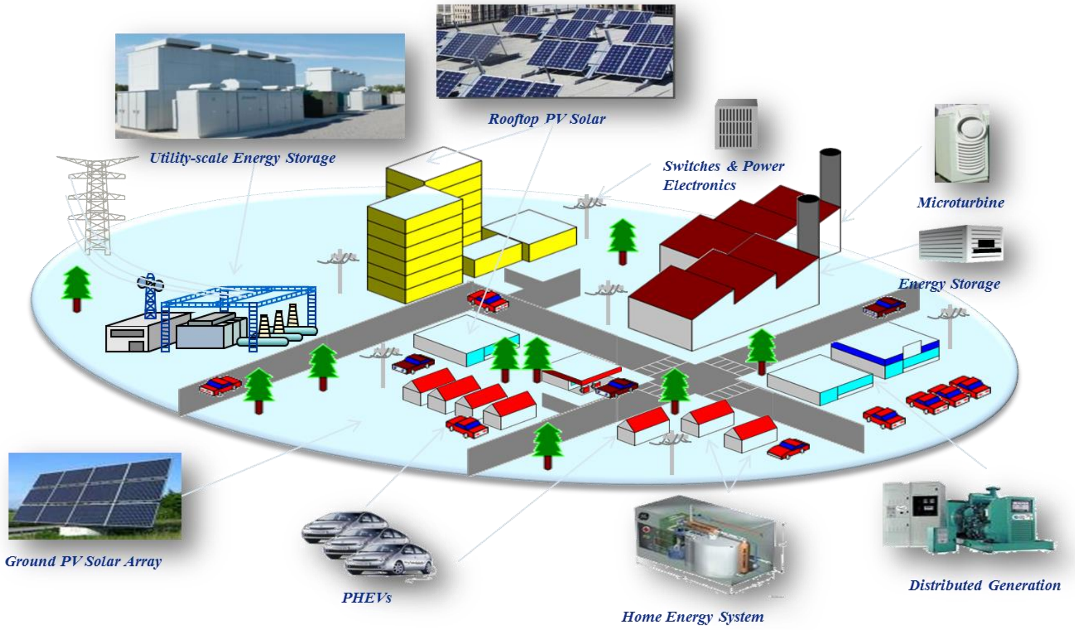


Rovers and Lunar Science
- Polar Resources Ice Mining Experiment-1 (PRIME-1)
  - Robotically sample and analyze for ice from below the surface.
- Volatiles Investigating Polar Exploration Rover (VIPER)
  - Explore terrain that is more or less likely to hold water.
- Power Demand: ~200 - 1000 Watts (nominal)

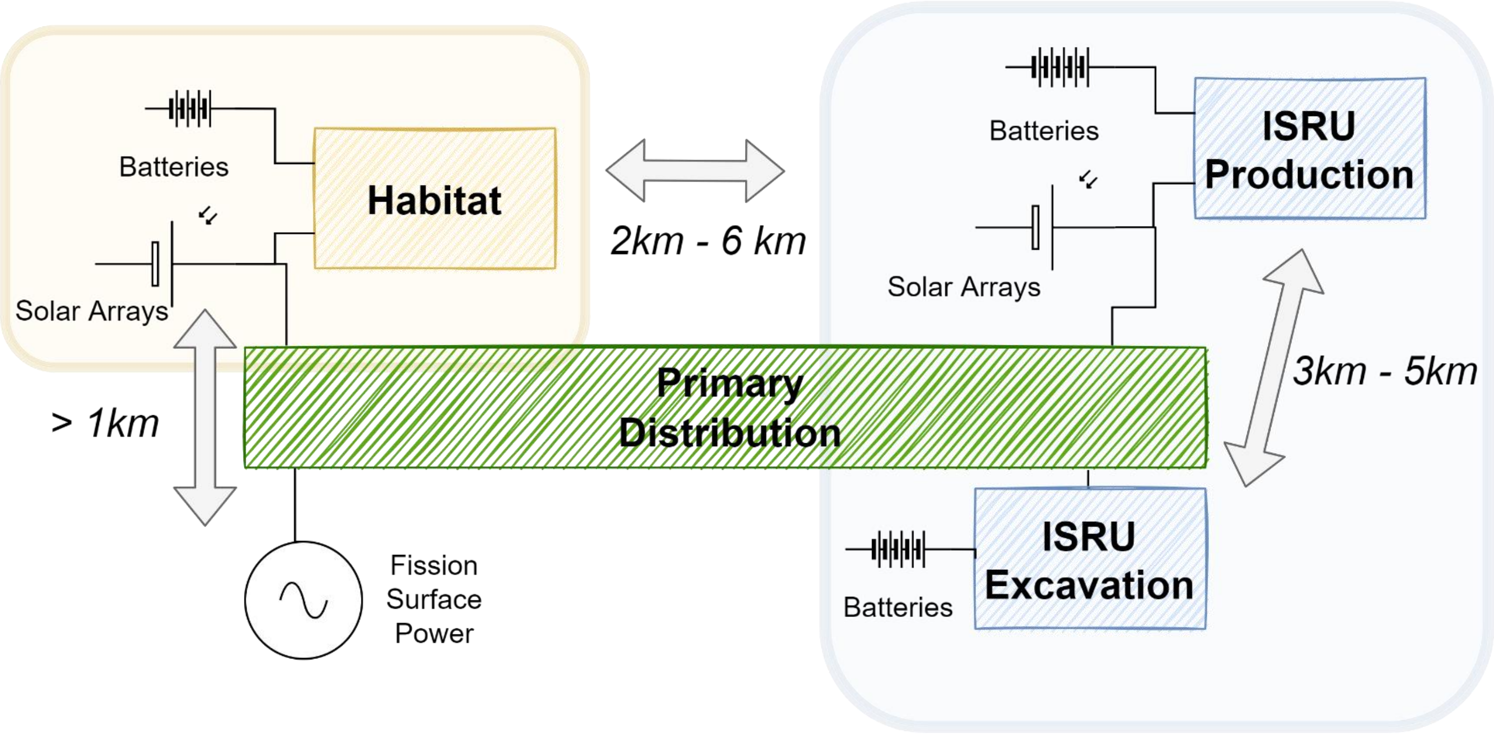
Case for a Lunar Power Grid

- **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**





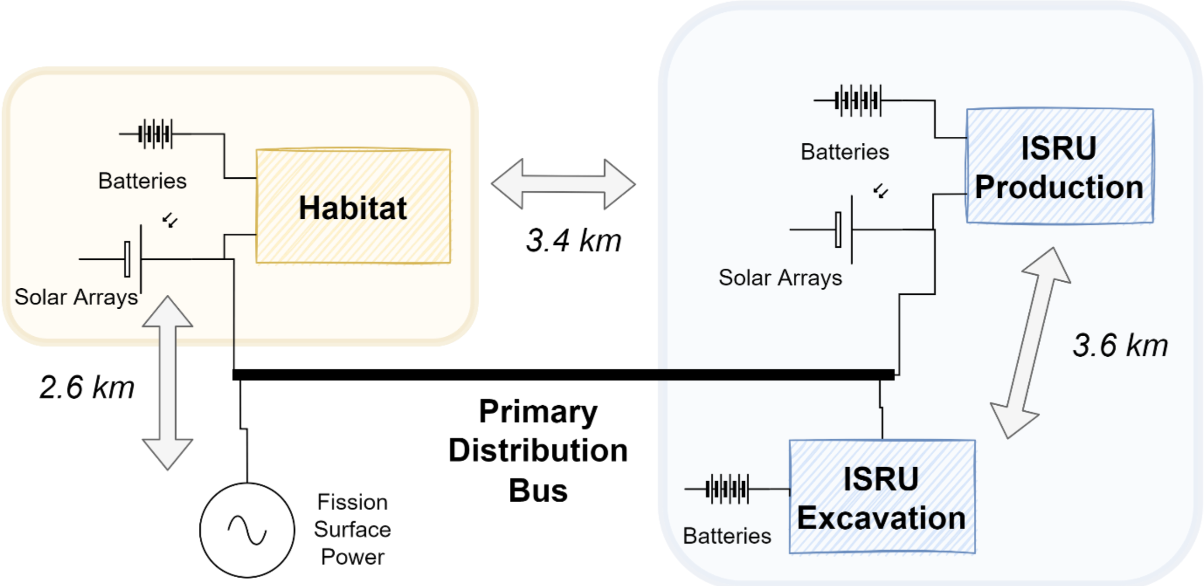
Notional Artemis Base Camp Microgrid



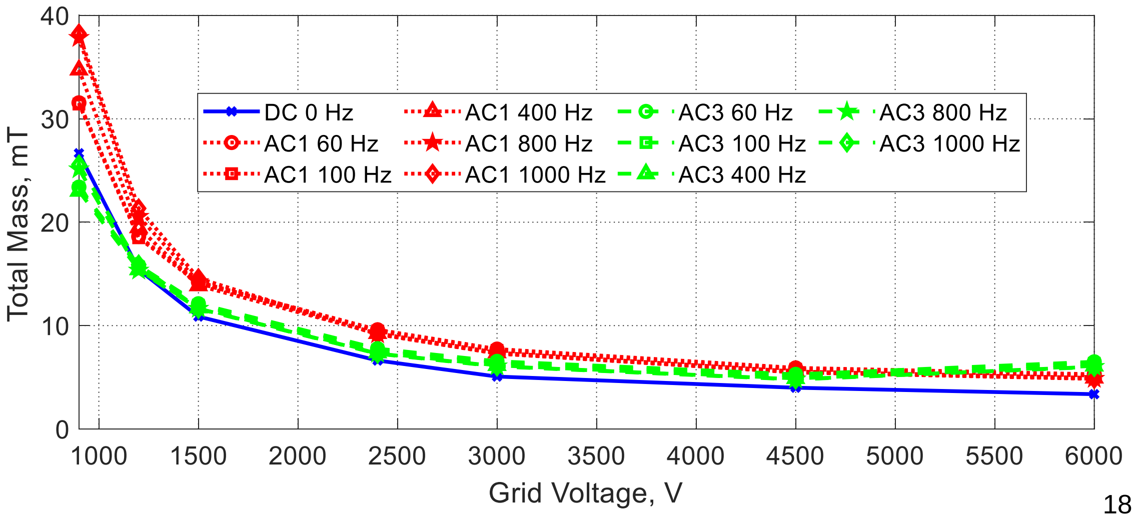
- **Lunar surface south microgrid**
  - Create local microgrids that can manage their own power
  - Primary distribution system to enable power sharing between local microgrids
  - Additional power sources (such as FSP) that can be utilized by and local microgrids
  - Additional power loads can connect 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: (600V – 6 kV)
  - Data contains estimated mass of converters + cables
- **Results**
  - Increasing voltage up to 3 kV has large mass advantages
  - AC vs DC at a single voltage is marginal
    - Especially higher voltages
  - Technology limitations need to considered
    - Max DC: 1.5 kV
      - Rad hard limitations
    - Max AC: none known



Radial Architecture



Microgrid Definition and Interface Converter for Planetary Surfaces (MIPS)

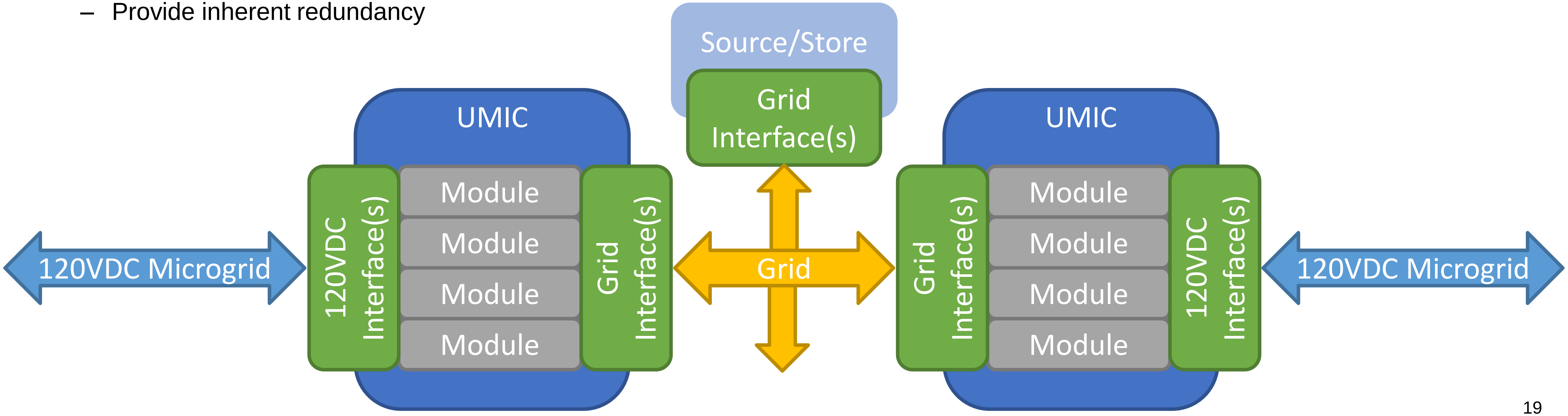
The MIPS Universal Modular Interface Converter (UMIC) is a power converter that provides bidirectional power flow between the power transmission voltage and the primary distribution voltage (120VDC), connecting islanded microgrids to form a grid.

The UMIC is truly modular, as modules can be easily:

- Replaced if damaged
- Relocated to more critical areas (reusable)
- Spared (extras/backups) at low mass and volume
- Paralleled to:
  - Increase total power capability (scalable)
  - Provide inherent redundancy

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*

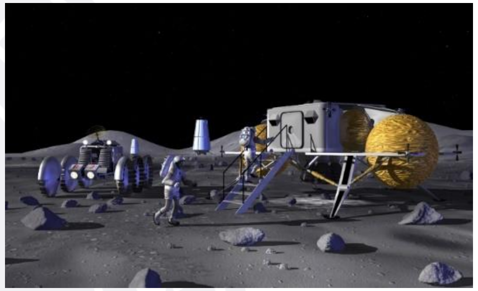
Objectives

- 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.**

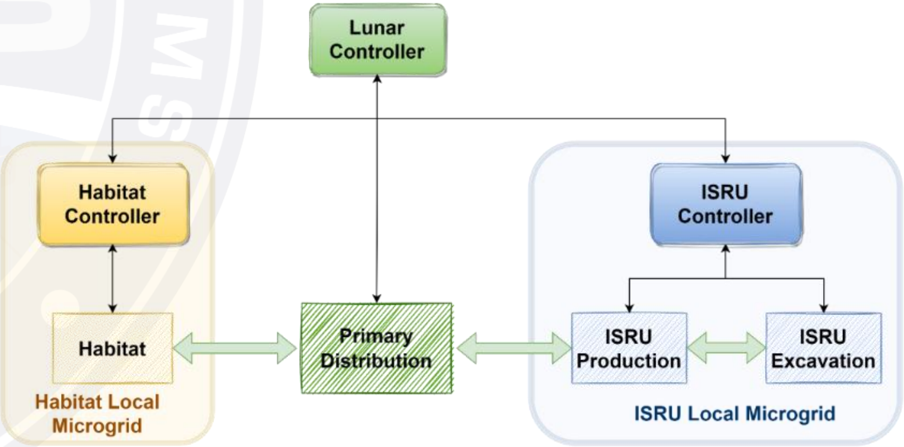
Lunar Surface Habitat



Demonstrate technology required for Mars Missions

Mars Surface Habitat

Communication latency time drives autonomous power needs



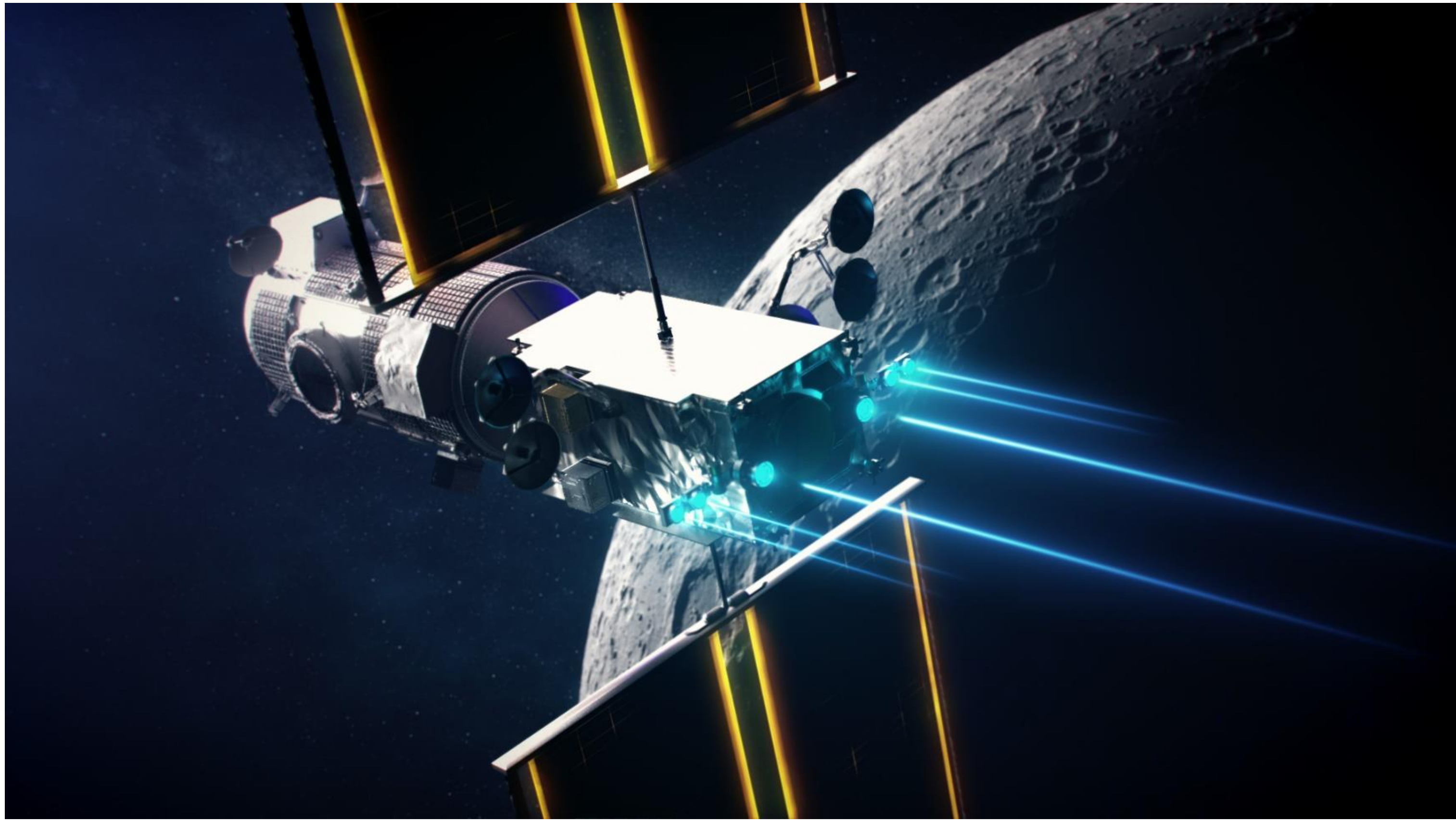
Hierarchical control architecture

Other NASA Space Power Projects

Gateway Power and Propulsion Element (PPE)

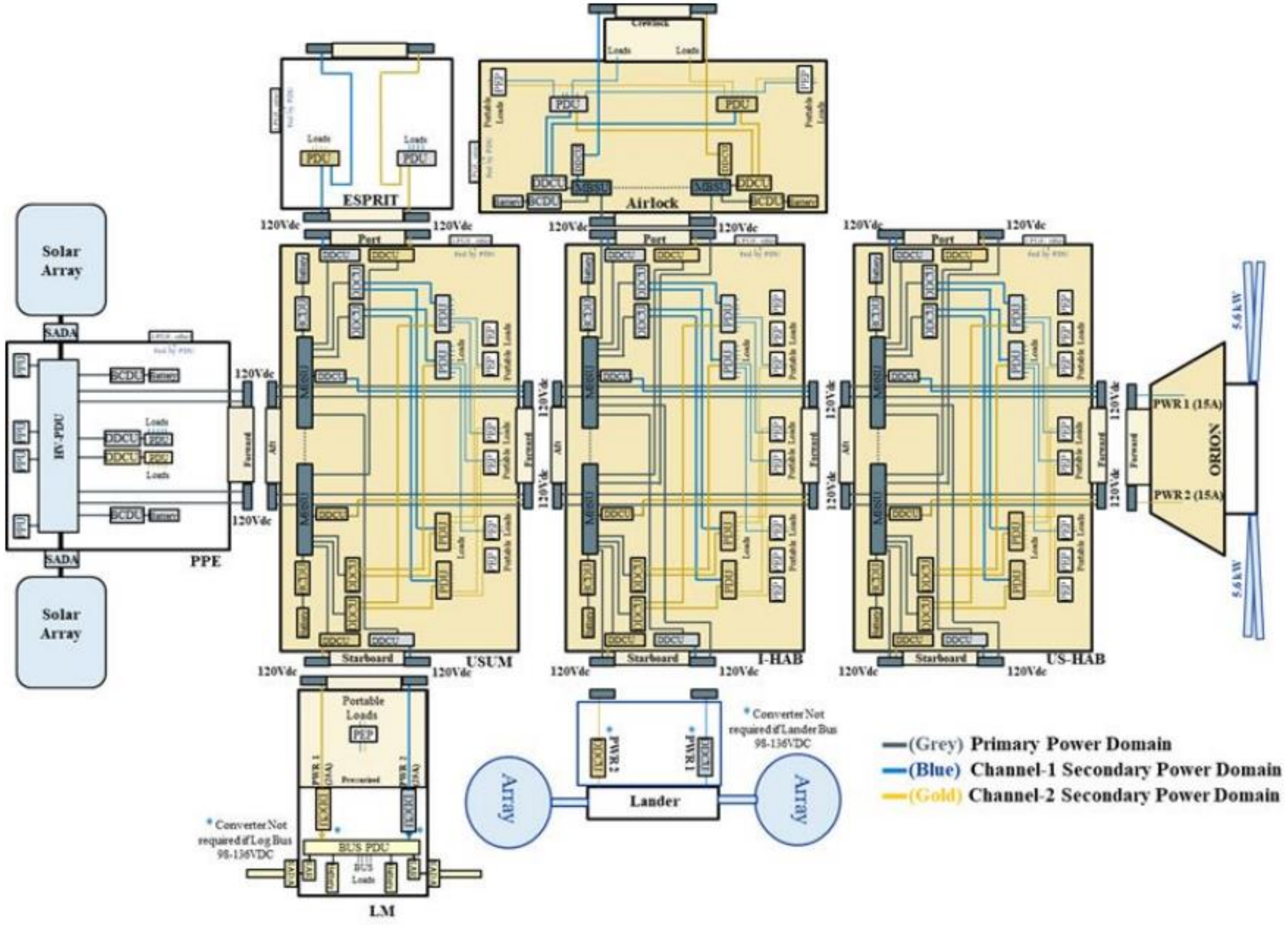
- Managed by NASA Glenn
- Build contracted to Maxar
- Launch co-manifested with HALO

- Provides 60+ kW of electric power
  - 52+ kW of solar array @ EOL
  - 16+ kW hrs. of Li-ion batteries
  - 100 VDC power distribution
  - 32 kW to rest of Gateway @ 120VDC
  - 48 kW to Thrusters
- 6 Ion Thrusters (2x12kW, 4x6kW)
  - 600 milli-Newtons of thrust
  - 0.135 lbs. of thrust
  - Xenon propellant
- Lifetime 15 years



Gateway Power

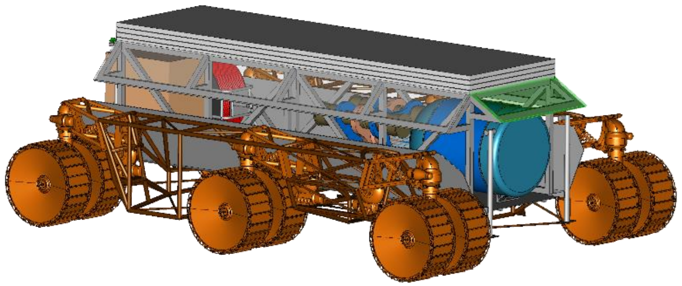
- **Fault Protection and Coordination**
  - Isolation
  - Reconfiguration
- **Energy Management**
  - Charge / Discharge Control
  - Battery State-of-Charge Balancing
  - Peak Shaving
- **Stability**
  - Small- and Large- Signal
  - Between Elements on Primary Bus
- **Analysis, Testing, and Verification**
  - Multiple providers at different stages of development
  - Various timescales depending on the power study



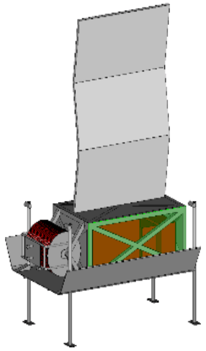
Conceptual Gateway Power System Architecture

Fission Surface Power (FSP)

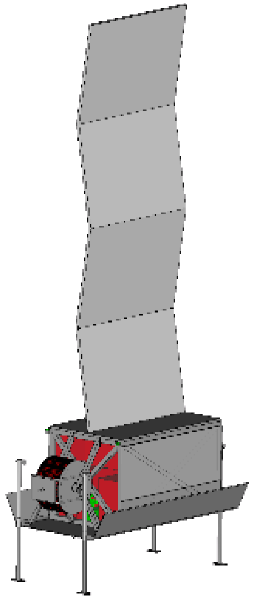
- **NASA and DOE are collaborating on the development of a 40 kWe fission surface power system for a demonstration on the moon by late 2020s with extensibility to Mars missions**
  - DOE has designated Idaho National Laboratory to manage development contracts. Los Alamos National Laboratory will provide 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 vaper heat pipe



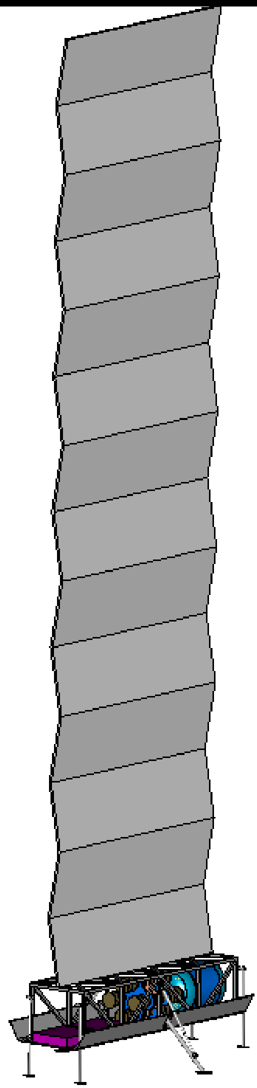
40 kW power system on lunar rover



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

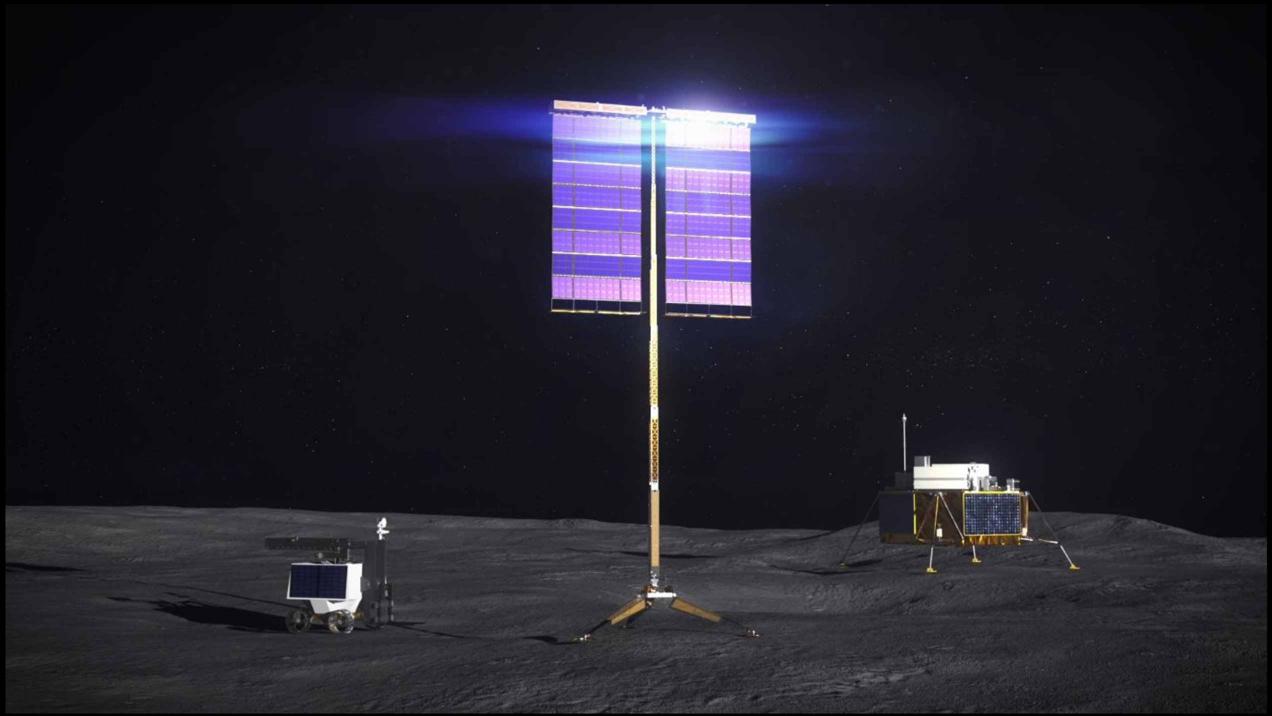


Photo credit: NASA

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.

Electrochemical Power Generation and Energy Storage

Power Generation

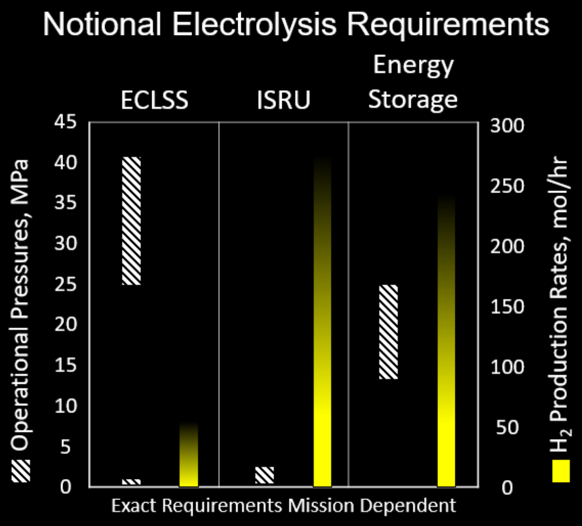
- *Fuel cells provide primary power to support DC electrical power bus*
  - *Use pure to propellant-grade O_2 / H_2 or O_2 / CH_4 reactants*
  - *Uncrewed experiment platforms*
  - *Crewed/uncrewed rovers*
  - *Electric aircraft / Urban Air Mobility (UAM)*
- *Applications*
  - *Mars/Lunar Landers (~ 2 kW to ≤ 10 kW)*
  - *Lunar/Mars surface systems (~ 2 kW to ≤ 10 kW modules)*
  - *Urban Air Mobility (120 kW to > 20 MW)*

NASA's all-electric X-57 Maxwell prepares for ground vibration testing at NASA's Armstrong Flight Research Center in California. Credits: NASA Photo / Lauren Hughes

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage.

Energy Storage

- *High specific energy (W·hr/kg) Regenerative Fuel Cells (RFC) to store and release both electrical & thermal energy*
  - *RFC specific energy 320 to 650 W·hr/kg depending on mission energy requirements (<u>Packaged</u> Li-ion batteries ~ 160 W·hr/kg)*
  - *Lunar night: ~100 hrs (south pole) to 367 hrs (equator)*
  - *Waste heat helps systems survive the lunar thermal environment (-173°C to +105°C)*
  - *Includes high pressure (O_2 = H_2 @ ≤ 2500 psia) and contaminated water electrolysis*
- *Applications*
  - *Crewed Lunar surface systems (36 kW·hr to ≥ 1 MW·hr)*
  - *Lunar sensor network (≤ 5 kW·hr)*

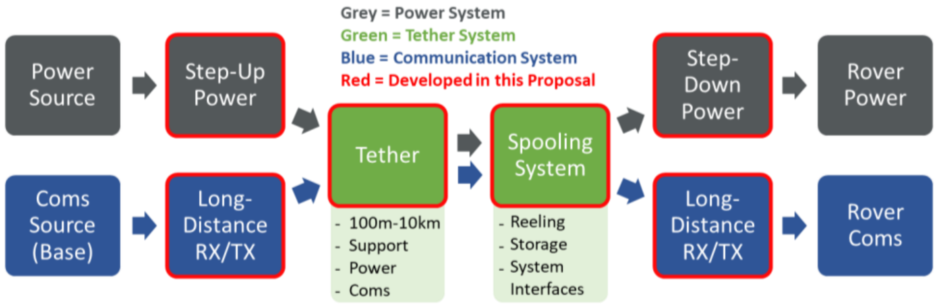


All applications Power and Mass Constrained

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:

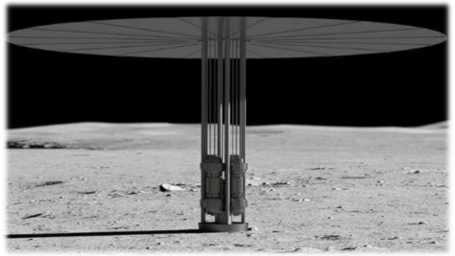
- Enable high-power transmission capabilities for nuclear or solar power systems
- Enable rover access to extreme terrain, like lunar craters, pits, caves, and lava tubes

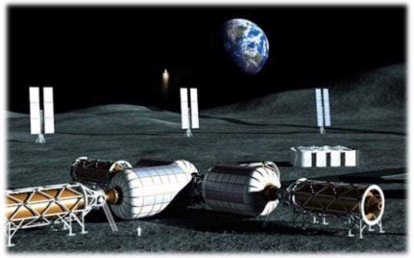


Key Performance Parameter	State-of-the –Art (SOA)	Threshold Value	Goal Value
Step-Up Converter Efficiency	90 %	92.5 %	97 %
Step-Down Converter Efficiency	N/A	92.5 %	97 %
Converter Power Density	0.3 W/cm^3	1 W/cm^3	2 W/cm^3
Converter Specific Power	250 W/kg	500 W/kg	1 kW/kg
End-to-End Efficiency	N/A	80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

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:

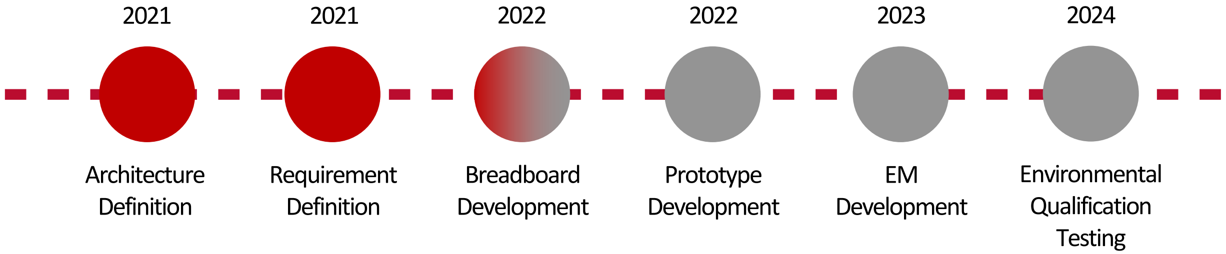
- Fission Surface Power and Surface Solar Power • 1 km • 10 kW • Fiber comms
- Moon Diver (Tethered Lunar Pit Descender) • 300 m • 100 W • Copper comms
- EELS (Enceladus Vent Crawler) • 3 km • 200 W • Fiber Comms
- PRIME (Europa Melt Probe) • 50 m • 200 W • Fiber coms
- FARSIDE (tethered telescope array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





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



Community Engagement

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

Working with NASA / Funding Opportunities

- **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/soliciations
  - NASA Research Opportunities
    - https://nspires.nasaprs.com/external/

Thank you