

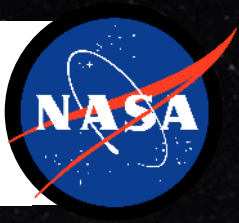


Power Needs and Challenges from the Moon to Mars

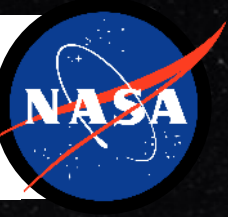
Virtual Presentation to TE Connectivity
Ottobrunn, Germany

Jeremiah McNatt | NASA Space Technology Mission Directorate

July 9, 2025



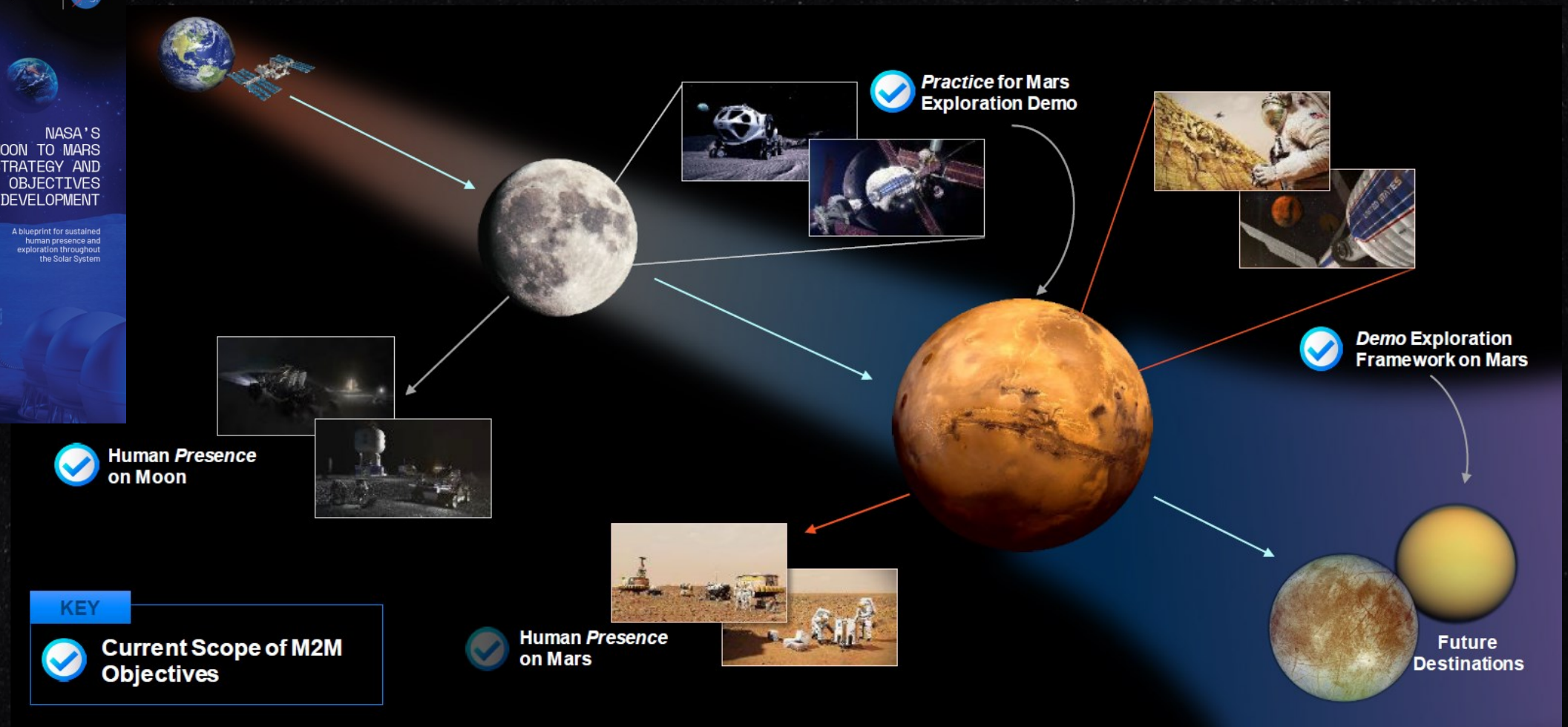
- The Roadmap to Mars and Beyond
- Designing a Strategic Architecture and Objectives
- An Envisioned Growth of Lunar Surface Power Assets
- Challenges to be Faced
- Addressing the Challenges through Technology Investment



NASA'S
MOON TO MARS
STRATEGY AND
OBJECTIVES
DEVELOPMENT

A blueprint for sustained
human presence and
exploration throughout
the Solar System

Released 6 April 2023





Human Lunar Return

Initial capabilities, systems, and operations necessary to re-establish human presence and initial utilization on and around the Moon.



Foundational Exploration

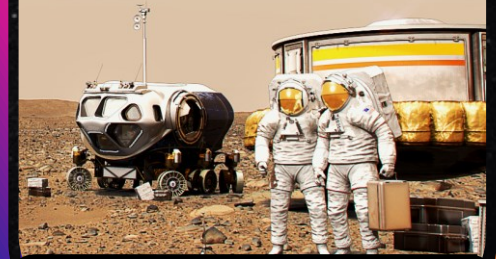
Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization and Mars forward precursor missions.



Sustained Lunar Evolution

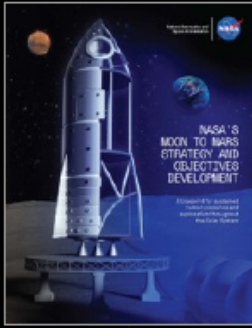
Enabling capabilities, systems, and operations to support regional and global utilization, economic opportunity, and a steady cadence of human presence on and around the Moon.

Future Segments

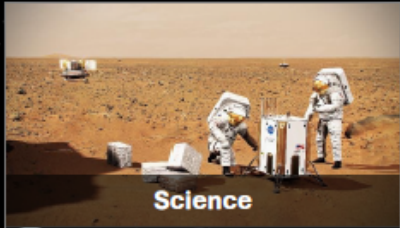


Humans to Mars

Initial capabilities, systems, and operations necessary to establish human presence and initial utilization on Mars and continued exploration.



Enabling Key Moon-to-Mars Lunar Infrastructure Objectives



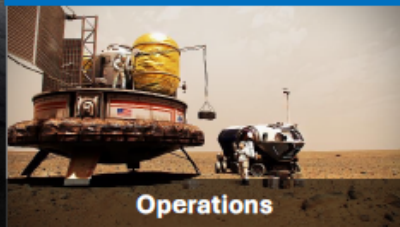
Science



Transportation & Habitation



Infrastructure



Operations

LI-1^L: Develop an incremental **lunar power**
MI-1^M 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.

LI-2^L: Develop a lunar surface, orbital, and
MI-2^M Moon-to-Earth **communications** architecture capable of scaling to support long term science, exploration, and industrial needs.

LI-3^L: Develop a **lunar position, navigation**
MI-3^M and **timing** architecture capable of scaling to support long term science, exploration, and industrial needs.

LI-4^L: Demonstrate **advanced manufacturing**
and **autonomous construction** capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-5^L: Demonstrate **precision landing** capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-6^L: Demonstrate local, regional, and global **surface** transportation and **mobility** capabilities in support of continuous human lunar presence and a robust lunar economy.

LI-7^L: Demonstrate industrial scale **ISRU** capabilities
MI-4^M in support of continuous human lunar presence and a robust lunar economy.

LI-8^L: Demonstrate technologies supporting cislunar orbital/surface depots, **construction** and **manufacturing** maximizing the use of in-situ resources, and support systems needed for continuous human/robotic presence.

LI-9^L: Develop **environmental monitoring**, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.



Artemis Campaign Elements

- NASA-led
- ~300 m transmission segments
- < 3 kW_e per element, ~40 kW total generation per site
- Possible external power augmentation



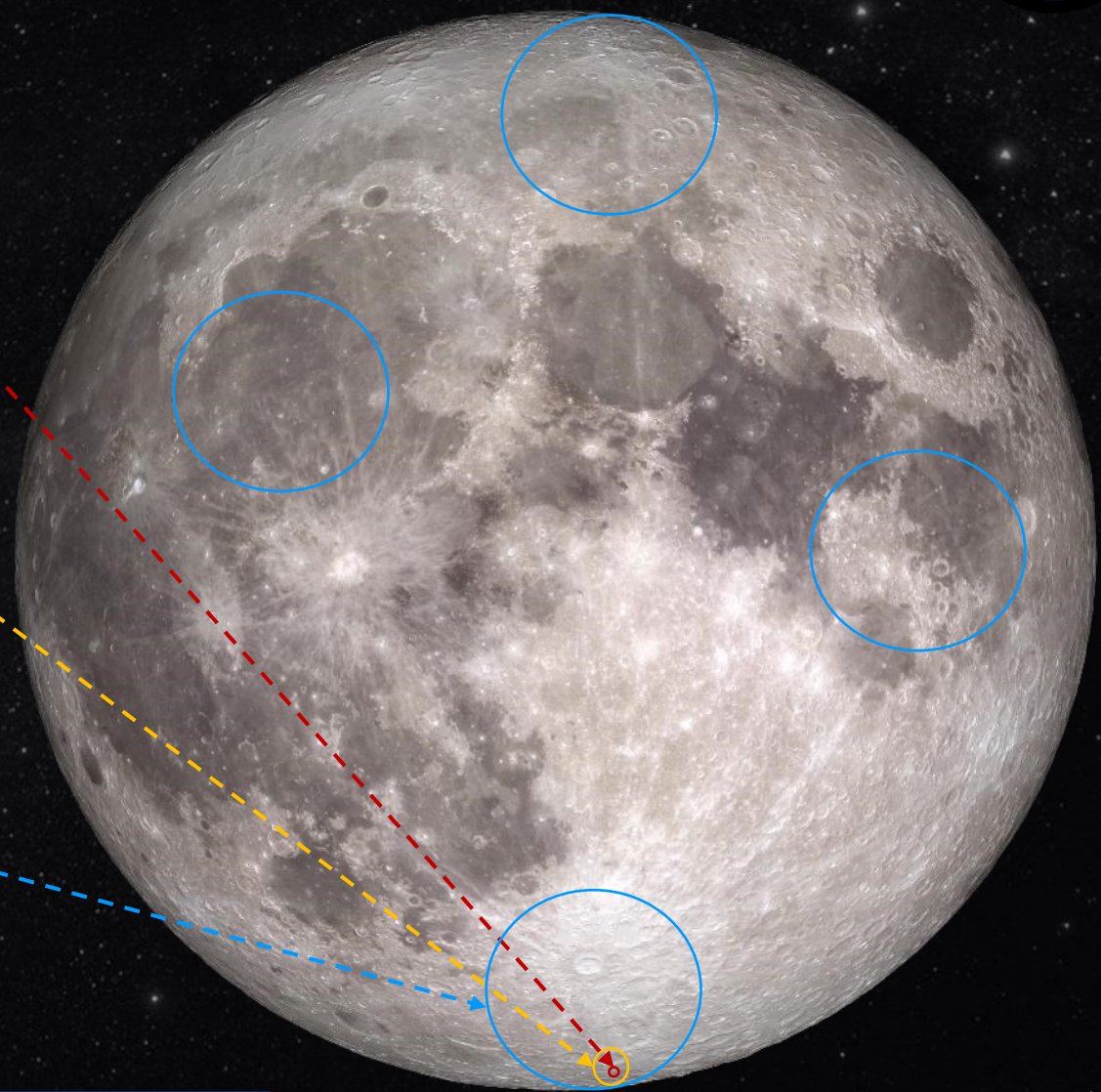
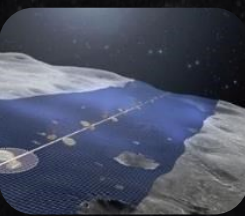
Polar Industrial-scale Infrastructure

- Industry-led with NASA supported technology
- Longer duration missions with higher power needs
- Resource prospecting, excavating, ISRU
- Possible ISRU Propellant Production
- ~15 km transmission segments
- ~2 MW_e total



Global Industrial Infrastructure

- Industry-led
- ISRU and facilities construction
- NASA is one of multiple customers procuring power and utilities
- Possible ISRU-sourced cables and photovoltaics
- ~1000 km transmission segments
- ~1+ GW_e total



COMMERCIAL SCALE WATER, OXYGEN, METALS & COMMODITY PRODUCTION



- Lunar resources mapped at meter scale for commercial mining
- 10's of metric tons of commodities per year for initial goal commercial usage
- Scalable to 100's to 1000's metric tons per year

COMMODITIES FOR HABITATS & FOOD PRODUCTION



- Water, fertilizers, carbon dioxide, and other crop growth support
- Crop production habitats and processing systems
- Consumables for life support, EVAs, and crew rovers/habitats for growing human space activities

IN SITU DERIVED FEEDSTOCK FOR CONSTRUCTION, MANUFACTURING, & ENERGY

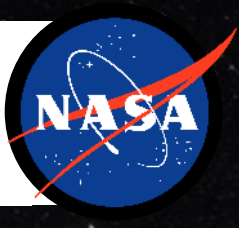


- Initial goal of simple landing pads and protective structures
- 100's to 1000's metric tons of regolith-based feedstock for construction projects
- 10's to 100's metric tons of metals, plastics, and binders
- Elements and materials for multi-megawatts of energy generation and storage
- Recycle, repurpose, and reuse manufacturing and construction materials & waste

COMMODITIES FOR COMMERCIAL REUSABLE IN-SPACE AND SURFACE TRANSPORTATION AND DEPOTS



- 30 to 60 metric tons per lander mission
- 100's to 1000's metric tons per year of for Cis-lunar Space
- 100's metric tons per year for human Mars transportation



Challenges for all power systems

- Mass/Volume
- Lifetime
- Technology Readiness
- Environmental Challenges
 - Illumination
 - Thermal
 - Radiation
- Varied Power Levels and Transmission Requirements

An abundant resource to produce power in space but scarce and/or limited on at the surface

Lunar Equatorial Illumination Limits

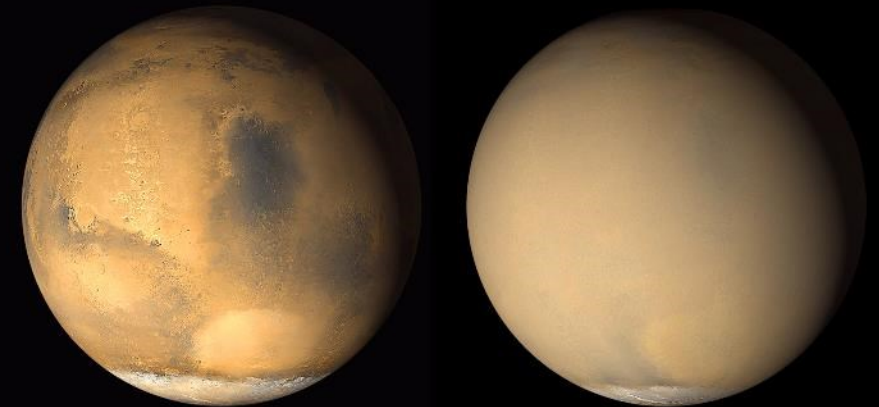
- Cyclical periods of 14 days illuminated, 14 days (340 hours) dark
- Consistent

Lunar Polar Illumination Limits

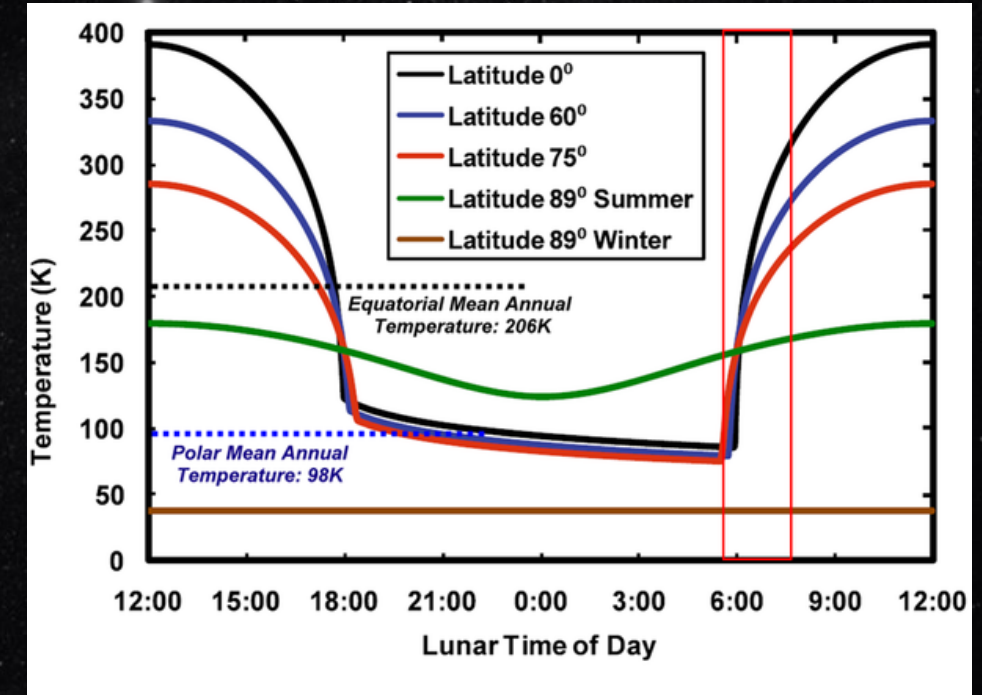
- High illumination sites exist but with intermittent (up to 3-day) periods of continuous darkness
- Highly dependent on location/elevation

Mars Surface Illumination Limits

- Global and Local dust storms decrease illumination as much as 95% in extreme cases

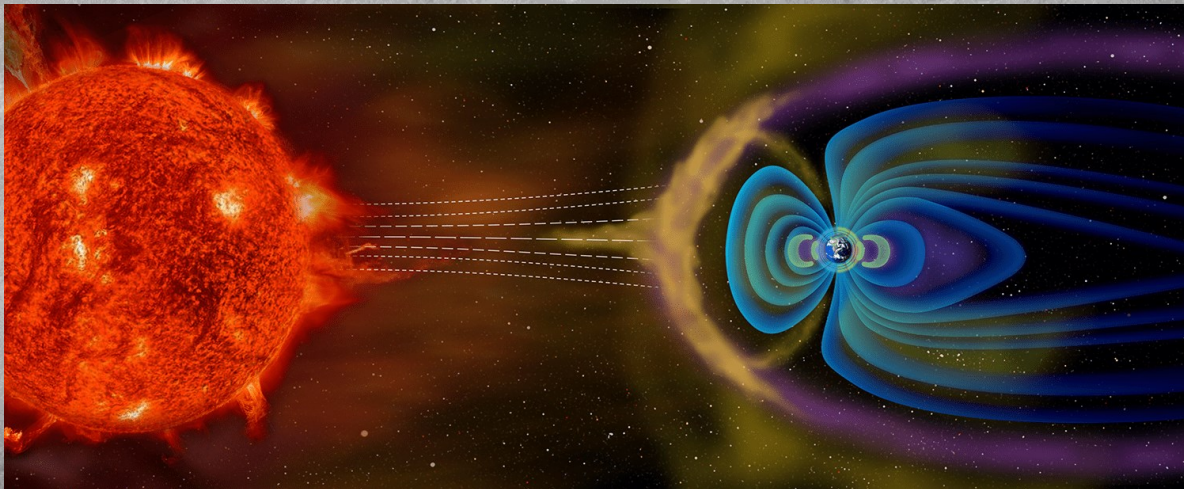


- Temperatures near the Moon's equator can spike to 250°F (121°C / 390 K) in daylight, then plummet after nightfall to -274°F (-170°C / 100 K).
- In deep craters near the Moon's poles, permanent shadows keep the surface even colder — NASA's Lunar Reconnaissance Orbiter has measured temperatures lower than -410°F (-246°C / 30K).

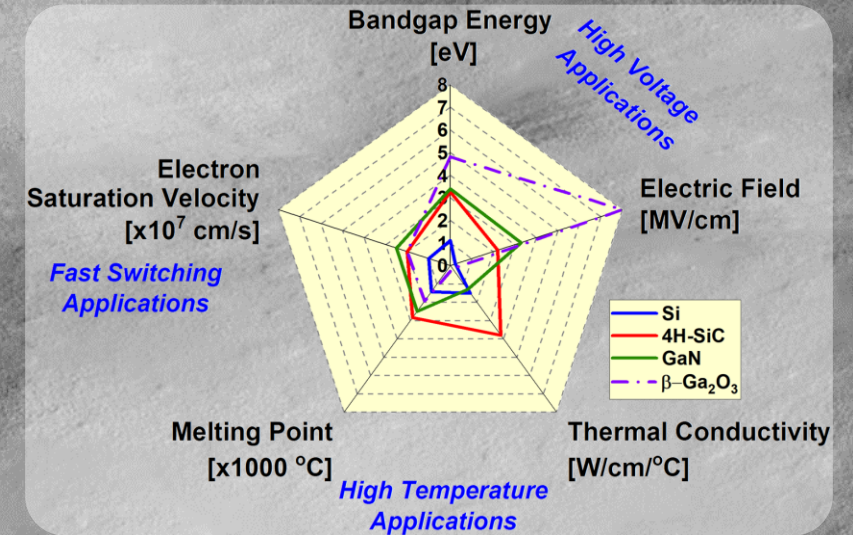


Systems in Lunar space do not benefit from shielding of energetic heavy ions by Earth's magnetic field.

- Single event effect (SEE) rates and displacement damage dose (DDD) levels are notably higher in Lunar space than in Low Earth Orbit
- Reliability of Wide-Band-Gap semiconductors operating at high voltages in the Lunar radiation environment is not fully understood
 - High voltage (AC or DC) is needed to transmit power over long distances



Need: High voltage, fast switching, high/low temperature operations



Historic Crewed Spacecraft

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

- Multi-kW_e-scale, unidirectional systems <150 VDC
- Experience base in LEO radiation environment
- Most loads considered “critical”
- Reliability guaranteed by redundancy via standards of operation (e.g., JSC-STD-8080)



Near Term - Artemis Flight Elements

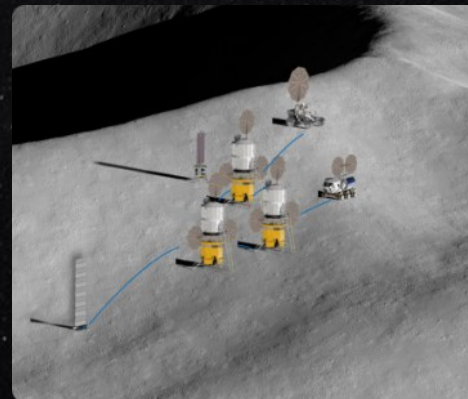
(e.g., Gateway, Orion, HLS)

- Multi-kW_e-scale mostly unidirectional systems (some bidirectional) < 150 VDC.
- Most loads considered “critical”.
- Reliability guaranteed by redundancy for critical loads



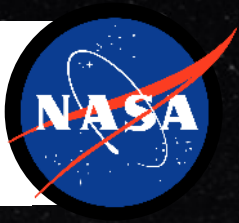
Next Step - Artemis Campaign Lunar Surface Elements

- Multi-kW_e-scale, unidirectional systems <150 VDC for most projected end states of base architecture
 - Higher voltage transmission may be applied in end states that engage the FSP for external augmentation.
- Artemis flight element reliability management scheme to be extended to surface elements where appropriate



Future State - Lunar Power Grid

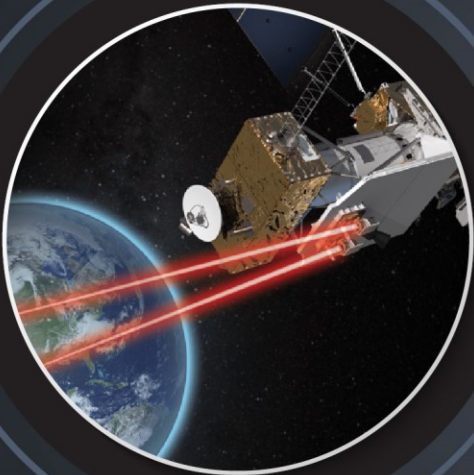
- MW_e-scale, uni- and bi-directional systems ranging from 150V to 1kV levels
 - Higher voltage transmission for long distances
- Multiple users/interfaces, interoperability needed
- May include ISRU derived elements



- The NASA Space Technology Mission Directorate (STMD) is advancing technologies and testing new capabilities that support Artemis and the Moon to Mars Architecture
- STMD is the Civilian Tech Base for Space
- STMD supports technology development needs of NASA's Mission Directorates
- STMD's portfolio spans a range of discipline areas and technology readiness levels

NATIONAL TECH BASE FOR CIVIL SPACE

Space Tech leads the development, demonstration, and infusion of transformational space technologies that solve critical stakeholder needs



ADVANCE US space technology innovation and competitiveness in a global context



ENCOURAGE technology driven economic growth with an emphasis on the expanding space economy



INSPIRE and develop a diverse and powerful US aerospace technology community

NATIONAL TECH BASE FOR CIVIL SPACE

Ensuring American Global Leadership in Space Technology

Functional Domain Areas

Space
Transportation

Space to Surface
Operations

Surface Infrastructure and
Exploration

In-Space Infrastructure and
Discovery

Foundational
Capabilities

Advanced Propulsion

Landing
Heavy Payloads

Landing for Science
Exploration

Spacecraft
Platform Technologies

Cryogenic Fluid Management

Precision Landing

Atmospheric
ISRU

Lunar Surface
Innovation Initiative

Sustainable Power and Surface Utilities

In Situ Resource Utilization

Survival in Extreme Environments

Autonomous Excavation and Construction

Advanced Robotics and Autonomy

Low TRL Habitation Systems

NextGen Avionics
and Communications

Gateway

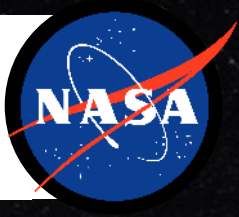
Commercial
Partners

Flight
Opportunities

Satellite Servicing
and Assembly

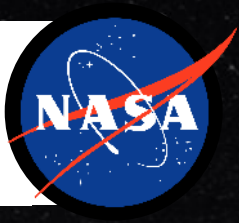
Small Spacecraft
Technologies

Advanced
Manufacturing



- NASA's Space Technology Mission Directorate (STMD) is refining its strategy for prioritizing technology investments
- A set of 187 shortfalls (identified technology areas that require further development) were established that encompass and expand the needs of each major technical area.
- NASA asked for feedback on these shortfalls at <https://spacetechpriorities.org/>
- The shortfall rankings were released in July 2024
- These shortfalls will be revised/updated based on ranking and feedback, expected on an annual basis
- 8 shortfalls were established for Power





Generate

- High Power Energy Generation on Moon and Mars Surfaces
- Power for Non-Solar-Illuminated Small Systems
- Lunar Surface Power Generation from ISRU Derived Resources
- Martian Surface Power Generation from ISRU Derived Resources

Store

- Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars

Manage

- Power Management Systems for Long Duration Lunar and Martian Missions

Distribute

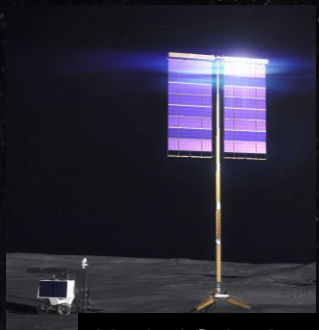
- High-Power, Long-Distance Energy Transmission Across Distributed Surface Assets
- Power and Data Transfer in Dusty Environments

High Power Energy Generation on Moon and Mars Surfaces

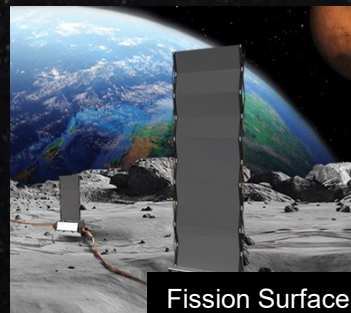
Meeting the need for a lunar surface power generation capability that is evolvable to support continuous robotic/human operation and is capable of scaling to global power utilization and industrial power levels. This shortfall includes solar and nuclear power generation capabilities. The primary function of these systems is the production of power, where the system is likely standalone, and may be deployed from or consist of a whole landed unit. These systems are envisioned to be able to be connected to local users and to a node within a power grid (interfaces, PMAD, and energy storage are captured in other capability goals).

Power for Non-Solar-Illuminated Small Systems

Small rovers, science landers, and resource prospecting systems would benefit from 50-100 We up to multi-100 We, sun-independent power sources. These missions may span from short duration to multiyear timelines. Longer term needs are to provide power to distributed sensor payloads for long duration science investigations. Static and dynamic radioisotope systems (DRPS) include an interest in development and testing of power conversion technologies that utilize alternative isotopes to plutonium.

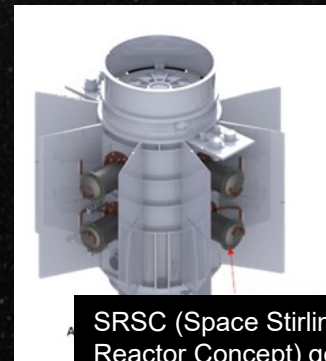


Vertical Solar Array Technology (VSAT) NASA Government Design



Fission Surface Power (FSP) System Concept

Ranked #2 of 187



SRSC (Space Stirling Reactor Concept) generator

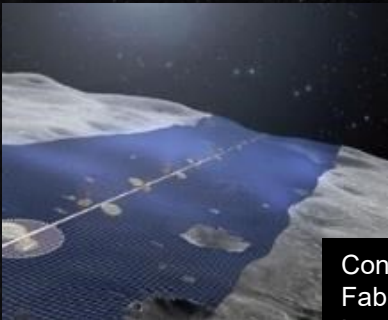
Ranked #27 of 187



Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) for NASA'S Mars 2020 Perseverance rover

Lunar Surface Power Generation from ISRU Derived Resources

ISRU based production of energy generation feedstocks and components will be necessary to grow a lunar economy and global industrial power grid. This shortfall addresses the need to develop technologies that use ISRU derived elements to create power components such as photovoltaics, cable, and battery anodes/cathodes).

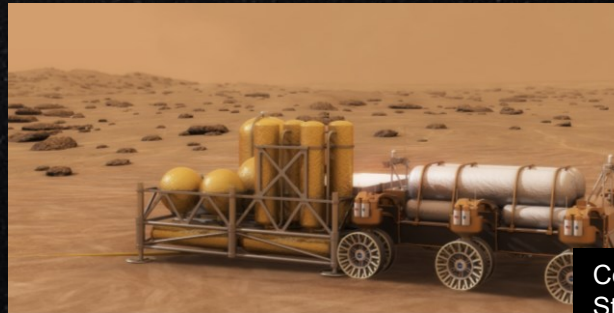


Concept of Silicon Solar Cells
Fabricated with Materials Extracted from
Lunar Regolith by ISRU Processes

Ranked #178 of 187

Martian Surface Power Generation from ISRU Derived Resources

Mars ISRU are expected produce methane and oxygen among others. These resources can be utilized to produce power through fuel cell systems. This shortfall addresses the need for the ability to efficiently convert liquid oxygen and liquid methane to power in a mass optimal solution for rovers and landers as a high reliable, scalable system.



Concept of a Mars ISRU Production and
Storage Facility

Ranked #183 of 187

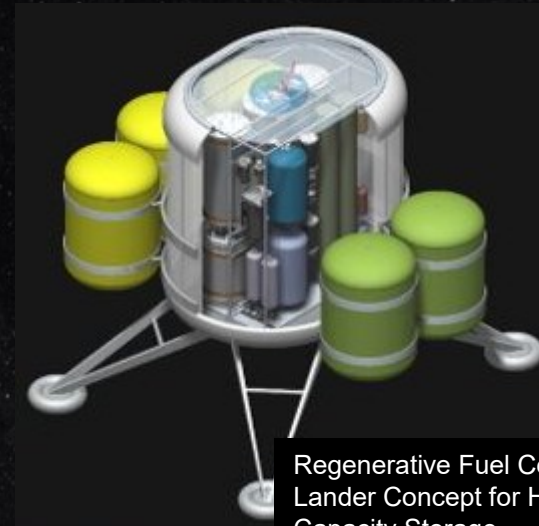
Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars

Energy storage technologies will be needed, and these systems will require high specific energy to reduce overall mass. Advanced chemistries and/or novel thermal materials/controls will be needed to allow for survival and operation during the lunar night.

These systems are envisioned to range from large energy storage systems to support extended eclipse/night survival/operations to mobile energy storage for human and robotic exploration of the lunar surface (small platforms, multi-purpose vehicles, EVA suits, tools and potentially operations in PSRs).

Understanding and monitoring the internal conditions these energy storage systems will help to ensure safety and reliability. This shortfall includes technologies that help to monitor the internal environment of energy storage systems.

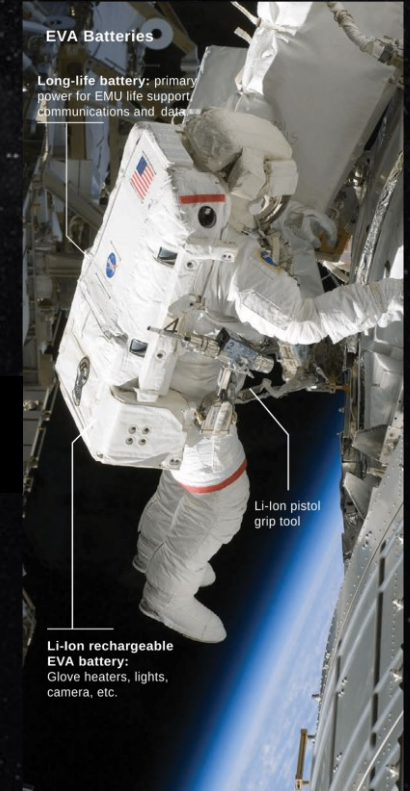
Ultra low temperature batteries can provide power for exploration into PSRs and other cold environments. Additionally, such technology could allow for hibernation for lunar night survival.



Regenerative Fuel Cell Lander Concept for High Capacity Storage



Battery Packs Used to Upgrade Hubble



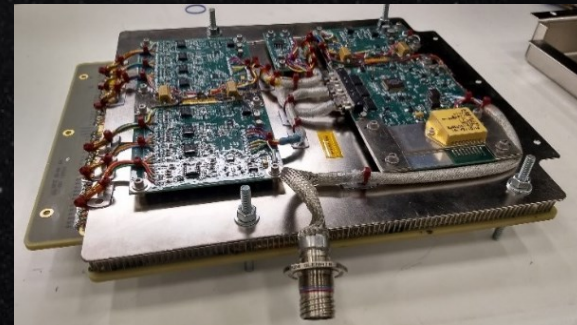
Small Scale Battery Technologies will Support Spacesuits and a Variety of Other Systems

Ranked #57 of 187

Power Management Systems for Long Duration Lunar and Martian Missions

Power management systems provide monitoring, control, and regulation to ensure sufficient power is available at all stages reliably throughout a mission. State of the art electronics do not provide sufficient durability to support long duration operations in the Lunar and Martian thermal, dust, and radiation environments and are not maintainable in those environment.

This shortfall addresses the need for power management subsystems built from common, interchangeable building blocks that can be used across multiple vehicles and surface elements would optimize spares and reduce maintenance impacts for long duration in-space operations.

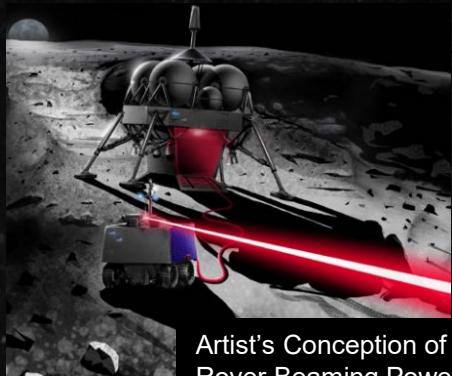


Power Management Electronics for a Lunar Surface Testbed

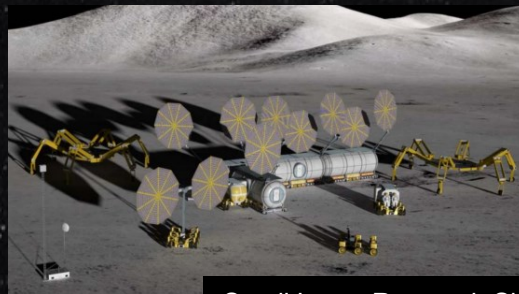
Ranked #12 of 187

High Power, Long Distance Energy Transmission Across Distributed Surface Assets

Common interfaces will allow for the distribution of power from generation source to user and bi-directional distribution among elements on the lunar surface. Both wired (cables, connectors) and wireless (power beaming) technologies may be suitable solutions to achieve this goal dependent on power level, distance, and environmental factors.. Radiation hardened power electronics and advanced power management and distribution systems will be necessary. All of these technologies will help lead to the development of a lunar power grid.



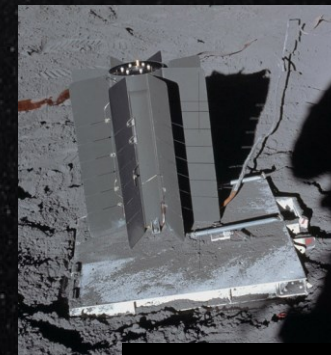
Artist's Conception of a Rover Beaming Power



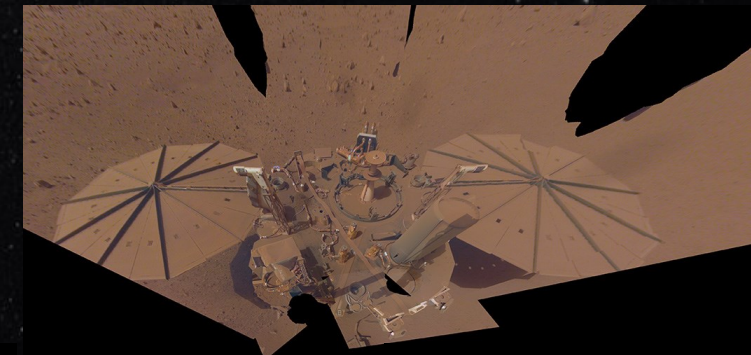
Small Lunar Research Site with a Local Power Grid

Power and Data Transfer in Dusty Environments

Lunar and Mars surfaces present challenges of dust migrating into and interacting with electrical connections. These connectors range in size and voltage and may include additional data transfer systems such as fiber optics. Connections may be made robotically or through crew assisted means.



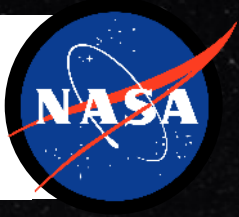
Apollo 14 RTG Covered in Dust



Mars Insight Lander Covered in Dust

Ranked #32 of 187

Ranked #34 of 187



- The Moon to Mars goals require Power Technology Research and Development
- The needs will evolve as the utilization of the lunar surface and its resources grow from early small landers and short human missions to potentially a global infrastructure of science, industry, and commerce
- There are many efforts underway addressing current and future needs but there are many more areas that will require attention and support
- NASA STMD is working to prioritize our investments to meet these needs and will continue to ask the community for feedback and prioritization

Thank You

