Lunar Surface Power Needs, Challenges, and Technologies

Virtual Presentation to The Ohio Federal Research Network (OFRN) Opportunity Days

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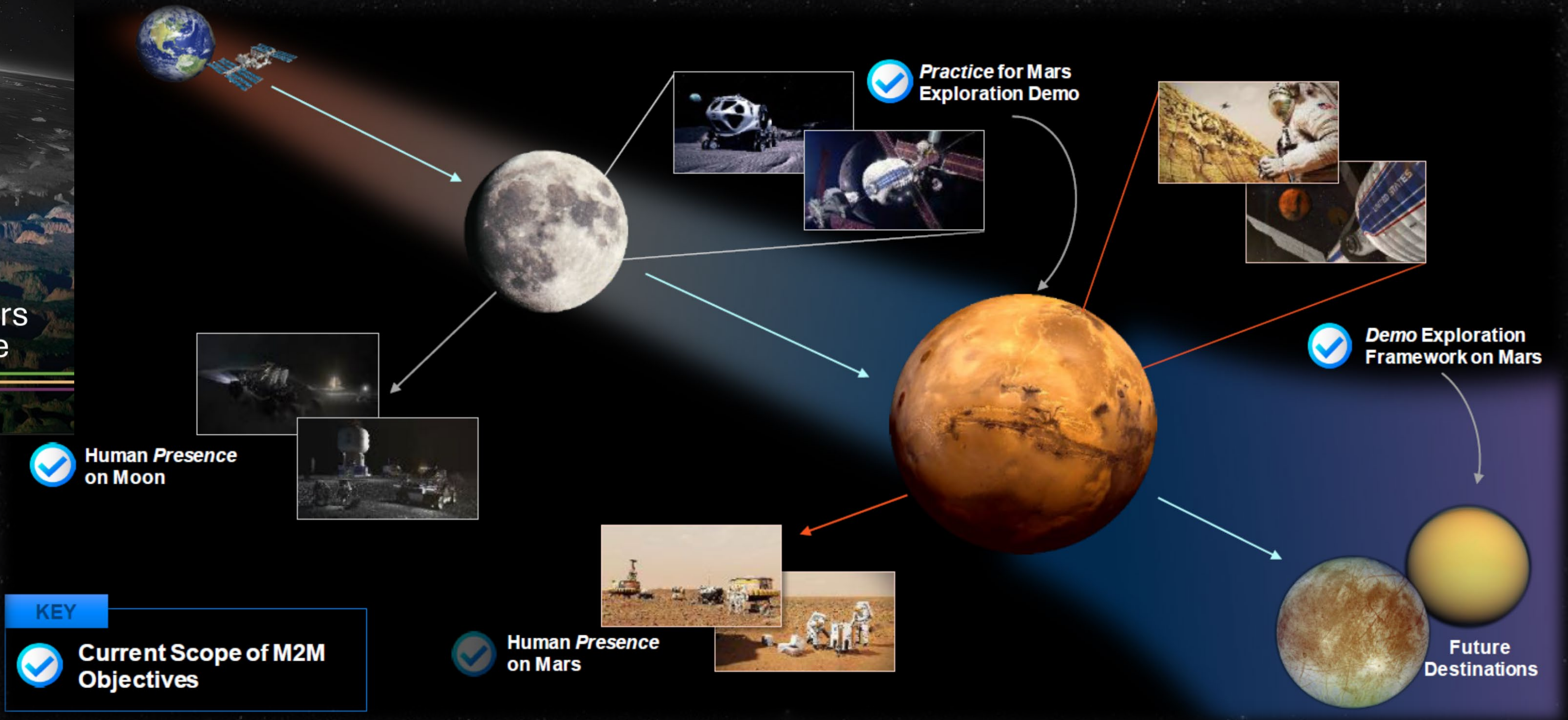
February 10, 2026

Big Picture: Moon to Mars



Architecture Segments

Future Segments

Human Lunar Return

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

Foundational Exploration

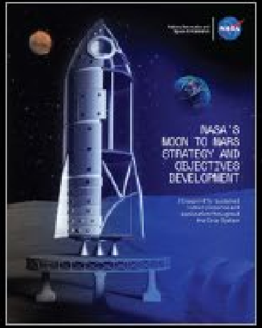
Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization and Mars forward precursor missions.

Sustained Lunar Evolution

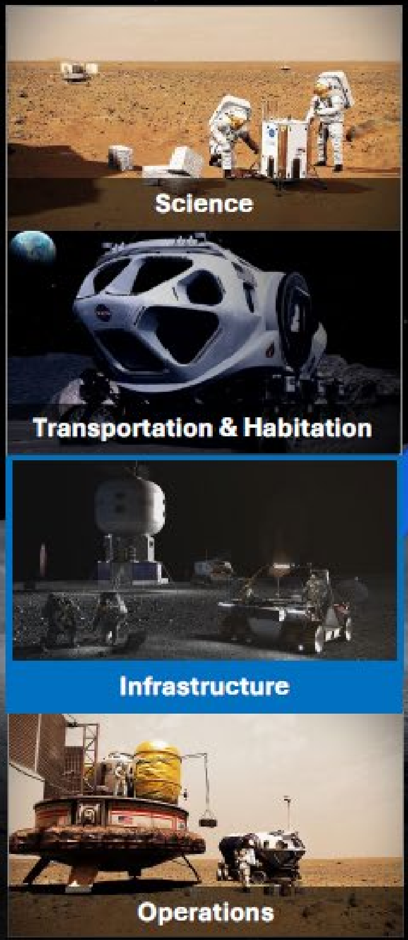
Enabling capabilities, systems, and operations to support regional and global utilization, economic opportunity, and a steady cadence of human presence on and around the Moon.

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



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.

The Benefits and Challenges of Illumination

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

Lunar Equatorial Illumination Limits

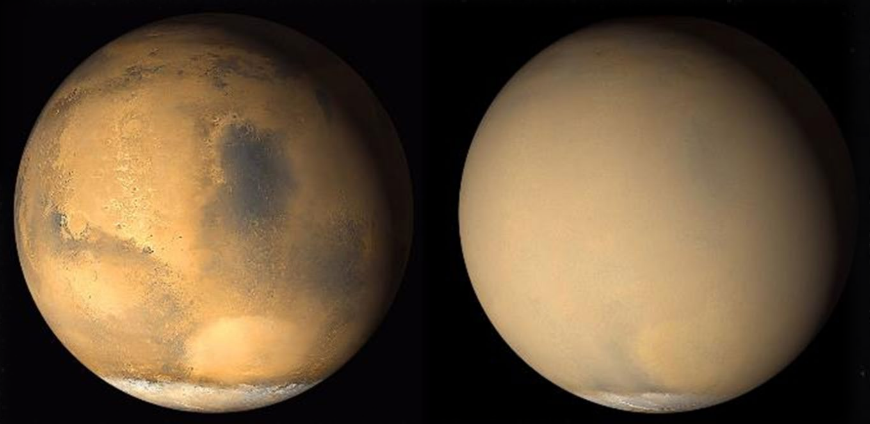
- Cyclical periods of 14 days illuminated, 14 days (*340 hours*) dark
- Consistent

Lunar Polar Illumination Limits

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

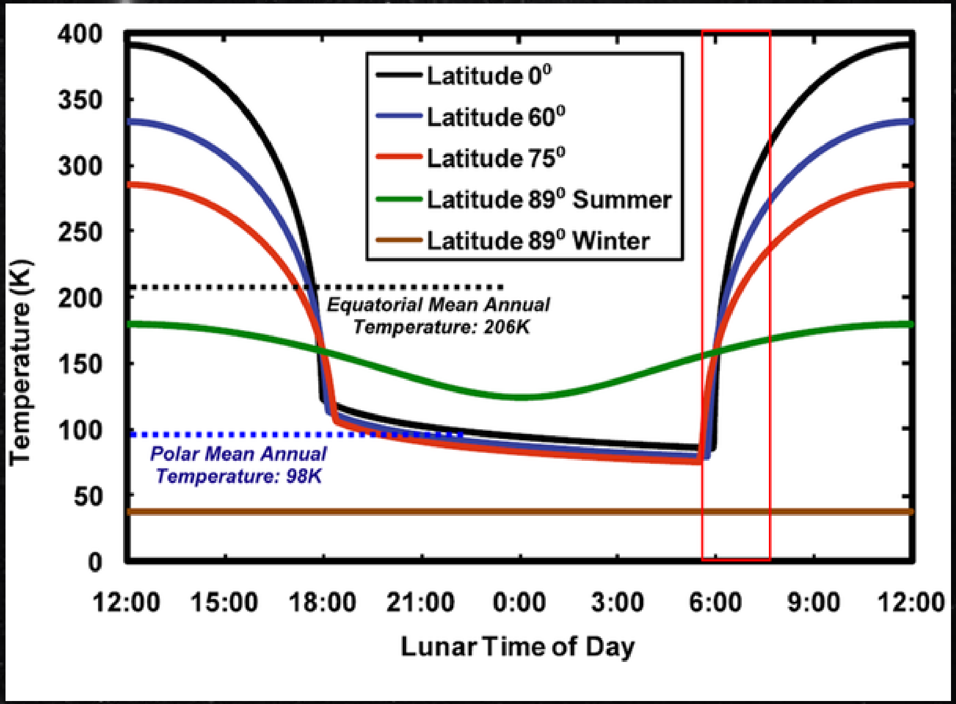
Mars Surface Illumination Limits

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



The Moon also has Unique Thermal Conditions

- 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).



NASA STMD's Role

- The NASA Space Technology Mission Directorate (STMD) is advancing technologies and testing new capabilities that support Artemis and the Moon to Mars Architecture

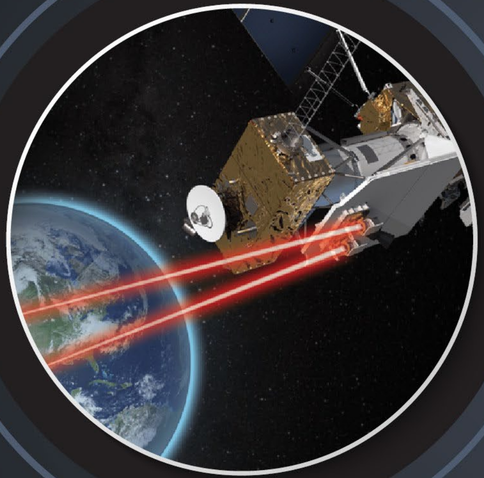
- STMD is the Civilian Tech Base for Space

- 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

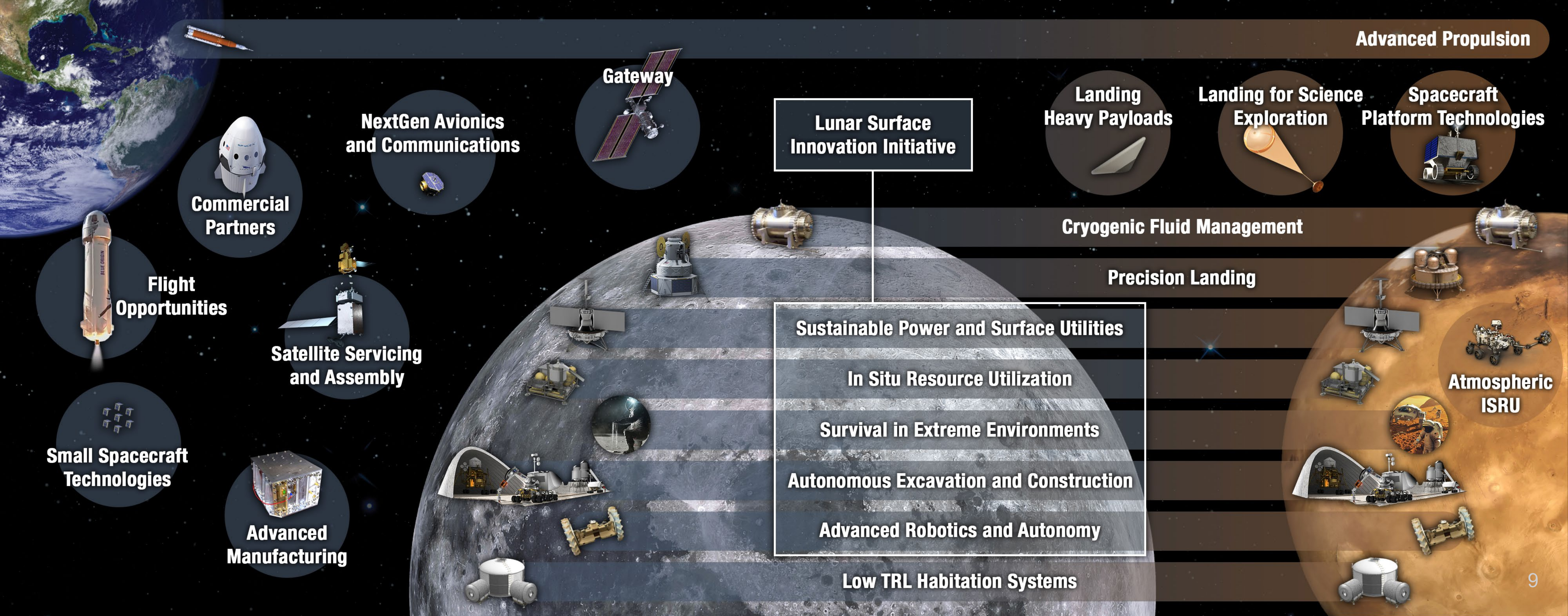
INSPIRE and develop a diverse and powerful US aerospace technology community

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



Surface Power Technology Development

- Advancing exploration on the Moon and Mars requires innovative development of new technologies and alignment of activities across NASA and with partners. Working with the community, we aim to rapidly develop, demonstrate, and deliver transformative capabilities
- Surface Power technologies include:
  - Power generation (e.g., solar arrays, primary fuel cells, nuclear and radioisotope systems)
  - Power management (e.g., advanced energy management system, power electronics)
  - Power distribution (e.g., cabling, connectors, power electronics, proximity charging, power beaming)
  - Energy storage (e.g., regenerative fuel cells, batteries)
- These technologies will provide the capability for continuous power throughout day and night operations on the lunar surface
- These systems will support operations with long discharge times, including applications on rovers, powering habitats, powering ISRU systems, astronaut vehicle systems

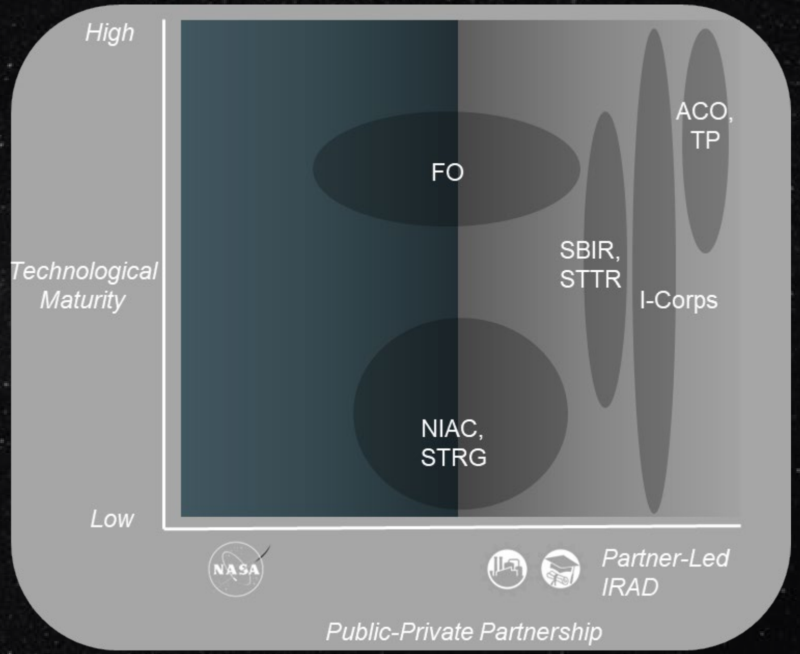
NASA's Innovation Pipeline

NASA's STMD advances U.S. leadership by delivering strong economic returns and strengthening domestic industry through its unique, collaborative role across the full technology development lifecycle.

Near-Term, Partner-led Research and Development: Industry or Academic Institution led research and development, leveraging NASA's facilities, expertise accessed through procurement and mutual agreements mechanisms to accelerate progress, offset and reduce costs. These efforts are designed to advance TRL and enable near-term mission infusion.

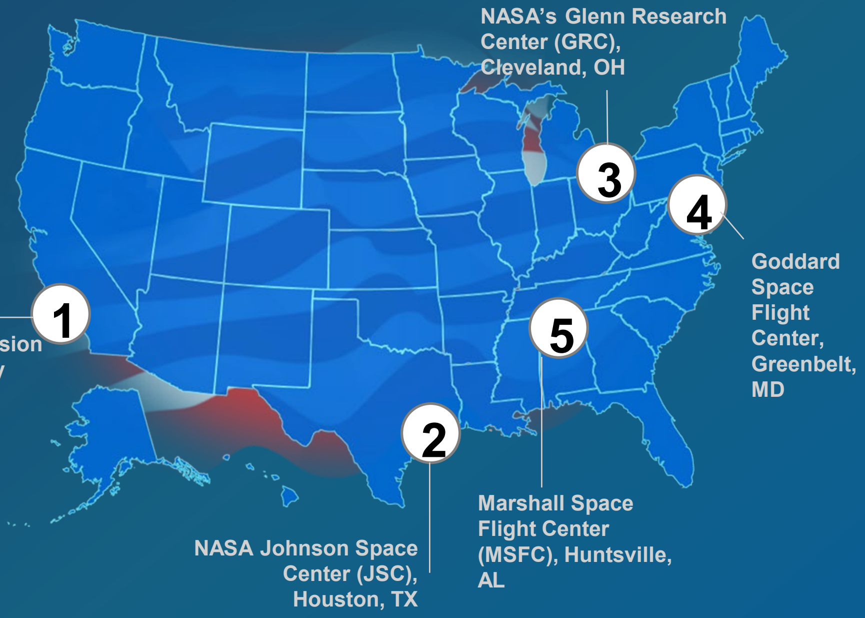
NASA uses a variety of specialized programs —each utilizing tailored procurement and agreement mechanisms to support innovation at specific stages of technology maturity. These programs include:

- NASA Innovative Advanced Concepts (NIAC)
- Space Technology Research Grants (STRG)
- Small Business Innovative Research (SBIR)
- Small Business Technology Transfer (STTR)
- Flight Opportunities (FO)
- Announcement of Collaborative Opportunity (ACO)
- Tipping Points (TP)



Through these mechanisms, NASA brings a powerful combination of institutional assets to its partnerships—*including world-class technical expertise and access to specialized facilities across its Centers*—enabling the development of transformative technologies with both space and terrestrial applications.

NASA Power Capability Facilities & Expertise Distribution



POWER GENERATION

Fission
- 3 Thermal Energy Conversion Branch
- 3 High Temperature and Smart Alloys Branch

Solar
- 3 Photovoltaic and Electrochemical Systems Branch
- 4 Power Systems Branch

Radioisotope
- 1 Electronics, Power Systems, and Technology
- 3 Thermal Energy Conversion Branch
- 3 High Temperature and Smart Alloys Branch

POWER MANAGEMENT & DISTRIBUTION

Power Electronics
- 1 Electronics, Power Systems, and Technology
- 3 Power Management and Distribution Branch
- 2 Power Systems Branch
- 2 Energy Systems Test Branch
- 4 Flight Data Systems & Radiation Effects Branch
- 4 Power Systems Branch

Cabling/ Connectors
- 2 Power Systems Branch
- 2 Energy Systems Test Branch
- 3 Power Management and Distribution Branch
- 1 Advanced Electronics Systems and Technology

Power Beaming
- 3 Photovoltaic and Electrochemical Systems Branch
- 2 Power Systems Branch
- 2 Energy Systems Test Branch
- 1 Advanced Electronics Systems and Technology

ENERGY STORAGE

Regenerative Fuel Cells
- 2 Energy Conversion Branch
- 2 Energy Systems Test Branch
- 3 Photovoltaic and Electrochemical Systems Branch

Batteries
- 2 Power Systems Branch
- 2 Energy Systems Test Branch
- 3 Photovoltaic and Electrochemical Systems Branch

Capacitors
- 2 Power Systems Branch
- 2 Energy Systems Test Branch
- 3 Photovoltaic and Electrochemical Systems Branch

FACILITIES SERVING MULTIPLE POWER CAPABILITIES

- 3 GRC: Propulsion System Lab (TVAC Systems)
  GRC: Microgravity facilities
  GSFC: TVAC Systems
- 4 JPL: TVAC Systems
- 1 JSC: TVAC Systems
- 2 MSFC: TVAC Systems
- 5 MSFC: Environmental Effects Facility

For more information on how to gain access for testing at NASA facilities, please visit https://www.nasa.gov/setmo/facilities/

Prioritizing Technology Investments

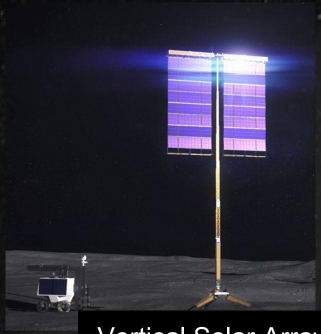
- NASA is refining its strategy for prioritizing technology investments to evolve into a stronger and more resilient tech base for civil space.
- The agency is collecting feedback through Feb. 20, 2026
- Input is essential to this process and our shared future success.
- NASA has identified a list of 32 technology shortfalls – technology areas requiring further development to meet future exploration, science, and other mission needs.
- How can you help? Please register and provide your feedback, so that you may help shape the technologies that enable tomorrow's missions. NASA is encouraging all U.S. businesses, organizations, agencies, and individuals with a vested interest in space technology to review the shortfall list and descriptions and submit feedback.
- NASA asked for feedback on these shortfalls at https://spacetechpriorities.org/

Thank You

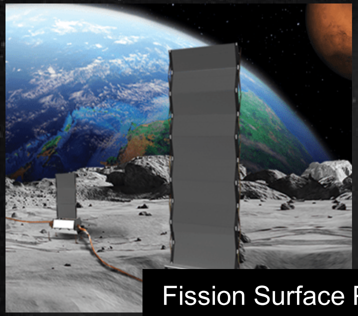
Energy Generation

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).



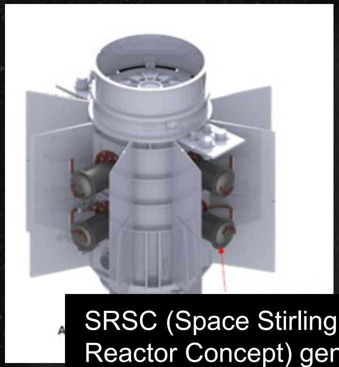
Vertical Solar Array Technology (VSAT) NASA Government Design



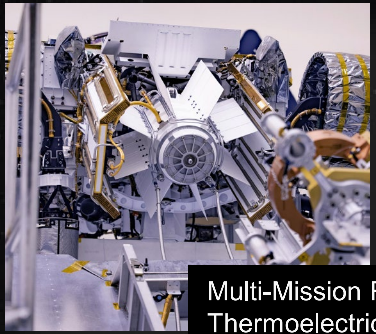
Fission Surface Power (FSP) System Concept

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.



SRSC (Space Stirling Reactor Concept) generator



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

Energy Storage

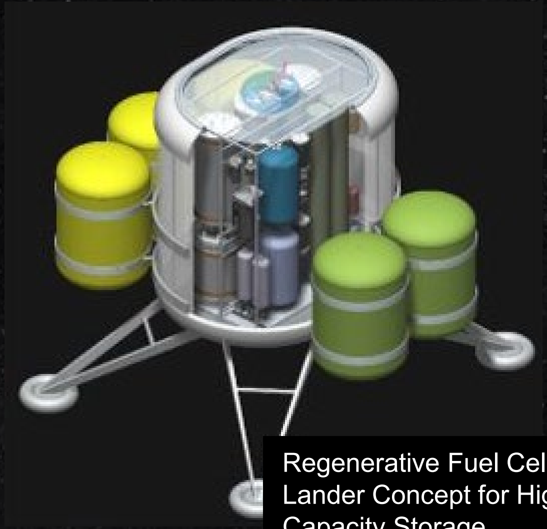
Energy Storage to Enable Robust and Long Duration Operations on Moon and Mars

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.

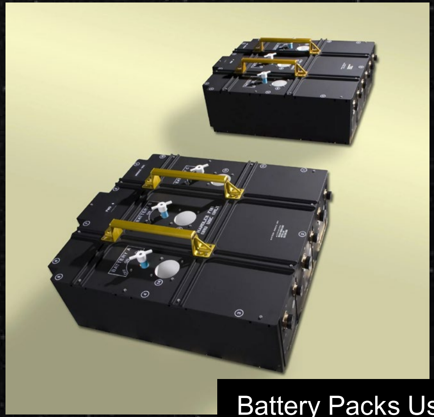
These systems are envisioned to range from large energy storage systems to support extended eclipse/night survival/operations to mobile energy storage for human and robotic exploration of the lunar surface (small platforms, multi-purpose vehicles, EVA suits, tools and potentially operations in PSRs).

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.

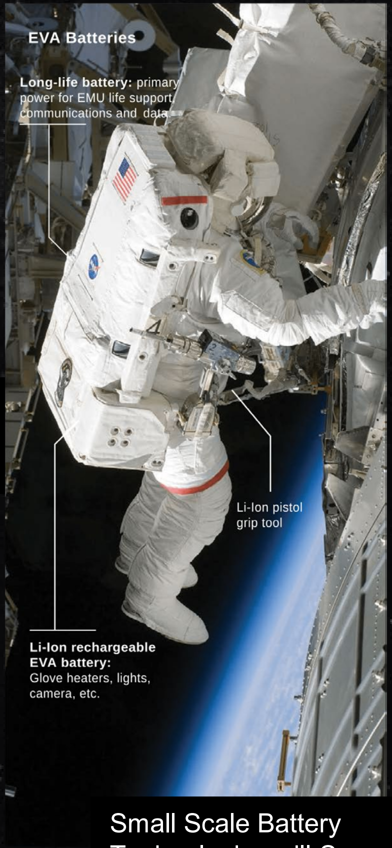
Ultra low temperature batteries can provide power for exploration into PSRs and other cold environments. Additionally, such technology could allow for hibernation for lunar night survival.



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

Power Management

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.

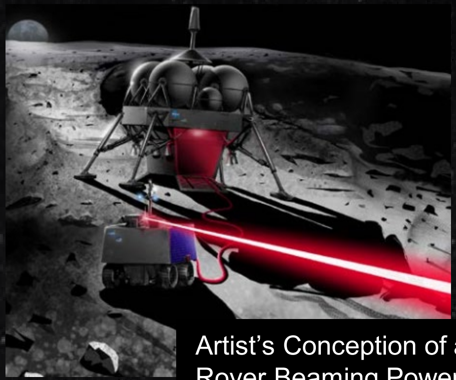
This shortfall addresses the need for power management subsystems built from common, interchangeable building blocks that can be used across multiple vehicles and surface elements would optimize spares and reduce maintenance impacts for long duration in-space operations.

Power Management Electronics for a Lunar Surface Testbed

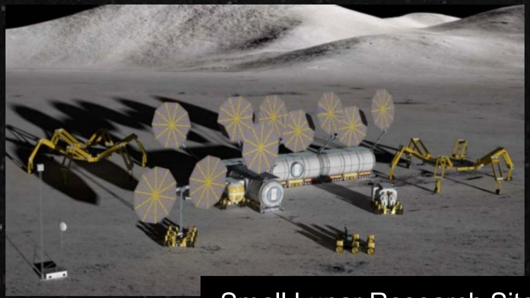
Power Distribution

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.



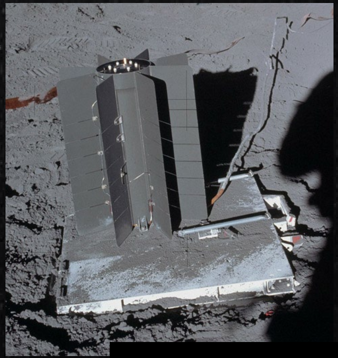
Artist's Conception of a Rover Beaming Power



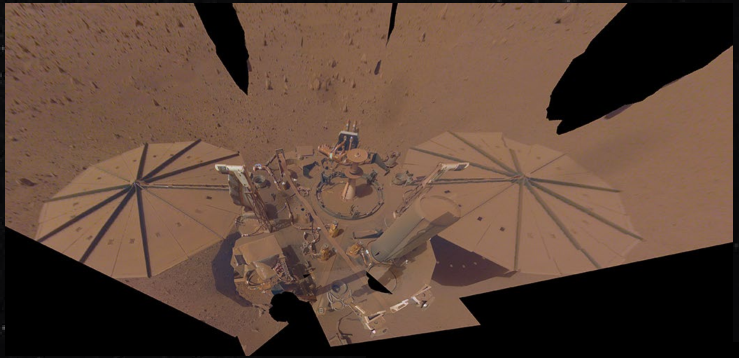
Small Lunar Research Site with a Local Power Grid

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