Note: Due to the rapid evolution of program schedules and mission plans, this presentation may include information that is no longer current.

Astromaterials Research and Exploration Science
Johnson Space Center

National Aeronautics and Space Administration

Powering the Lunar Surface: Managing Dust, Extreme Environments, and Power needs
ISDC 2026

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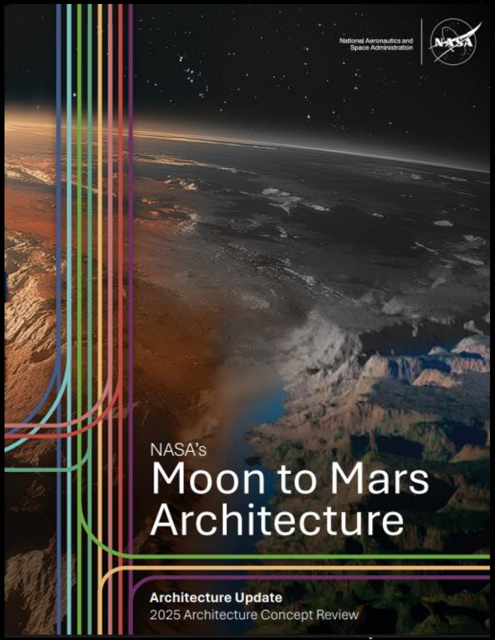
Previous: Test Engineer/Technology and Architecture Lead in JSC Propulsion and Power Division

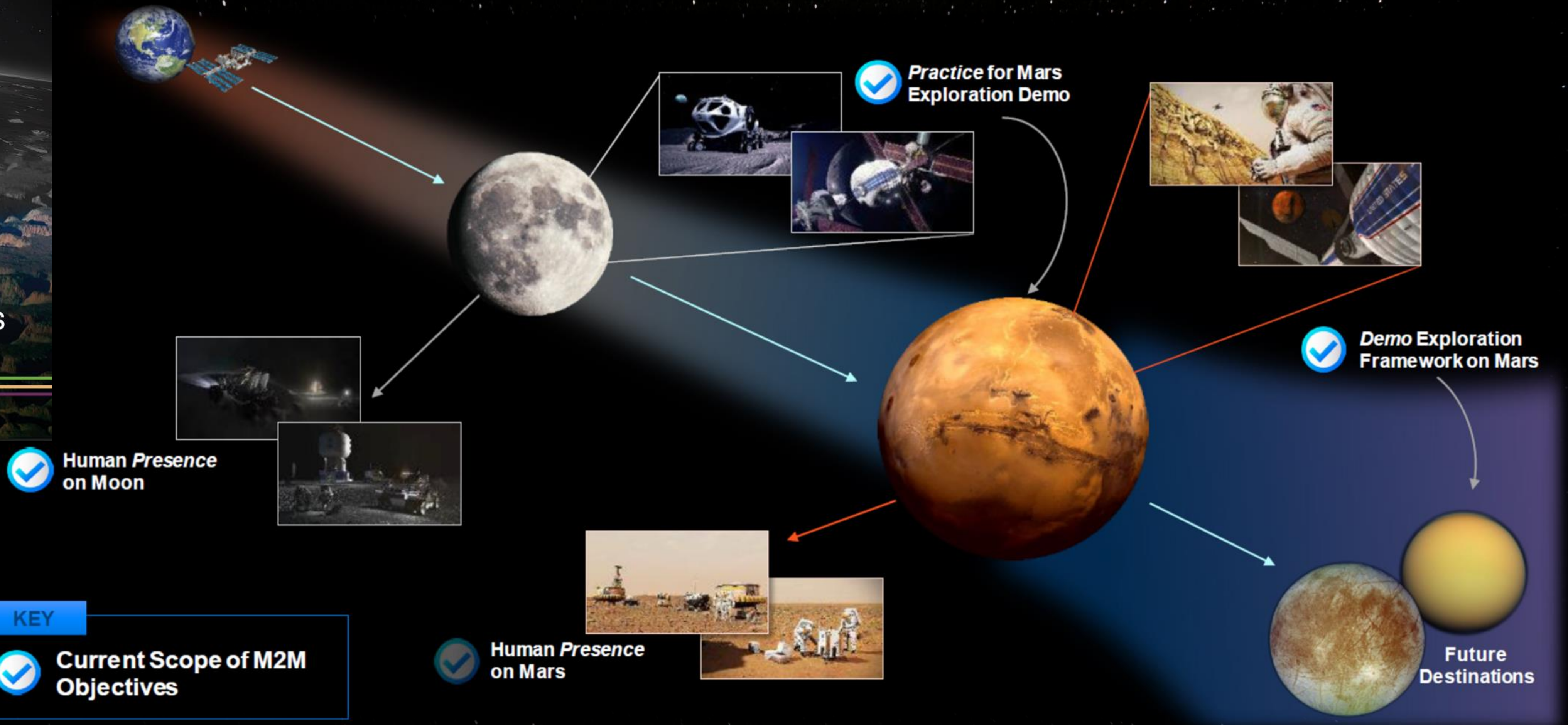
With contributions by:
Jeremiah McNatt, Principal Technologist of Power for STMD at GRC
Amber Turner, Scientist for Adnet Systems Inc at GSFC

Artificial Intelligence (AI) Usage Disclosure

This presentation was created with assistance from Copilot for editing the document for grammar and composing some of the sentences. The content has been reviewed and edited by Anastasia Ford.

Big Picture: Moon to Mars





McNatt, J. *Lunar Surface Power: Needs, Challenges, and Technologies* [PowerPoint slides]. NASA Space Technology Mission Directorate. (2026, February 10). Virtual presentation delivered to the Ohio Federal Research Network (OFRN) Opportunity Days.

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.

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Enabling Key Moon-to-Mars Lunar Infrastructure Objectives

- LI-1^{L} / MI-1^{M}: 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.
- LI-2^{L} / MI-2^{M}: Develop a lunar surface, orbital, and Moon-to-Earth **communications** architecture capable of scaling to support long term science, exploration, and industrial needs.
- LI-3^{L} / MI-3^{M}: Develop a **lunar position, navigation 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} / MI-4^{M}: Demonstrate industrial scale **ISRU** capabilities 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.

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Phase 1:

Secure reliable access to the surface and experiment

Starts now

Phase 2:

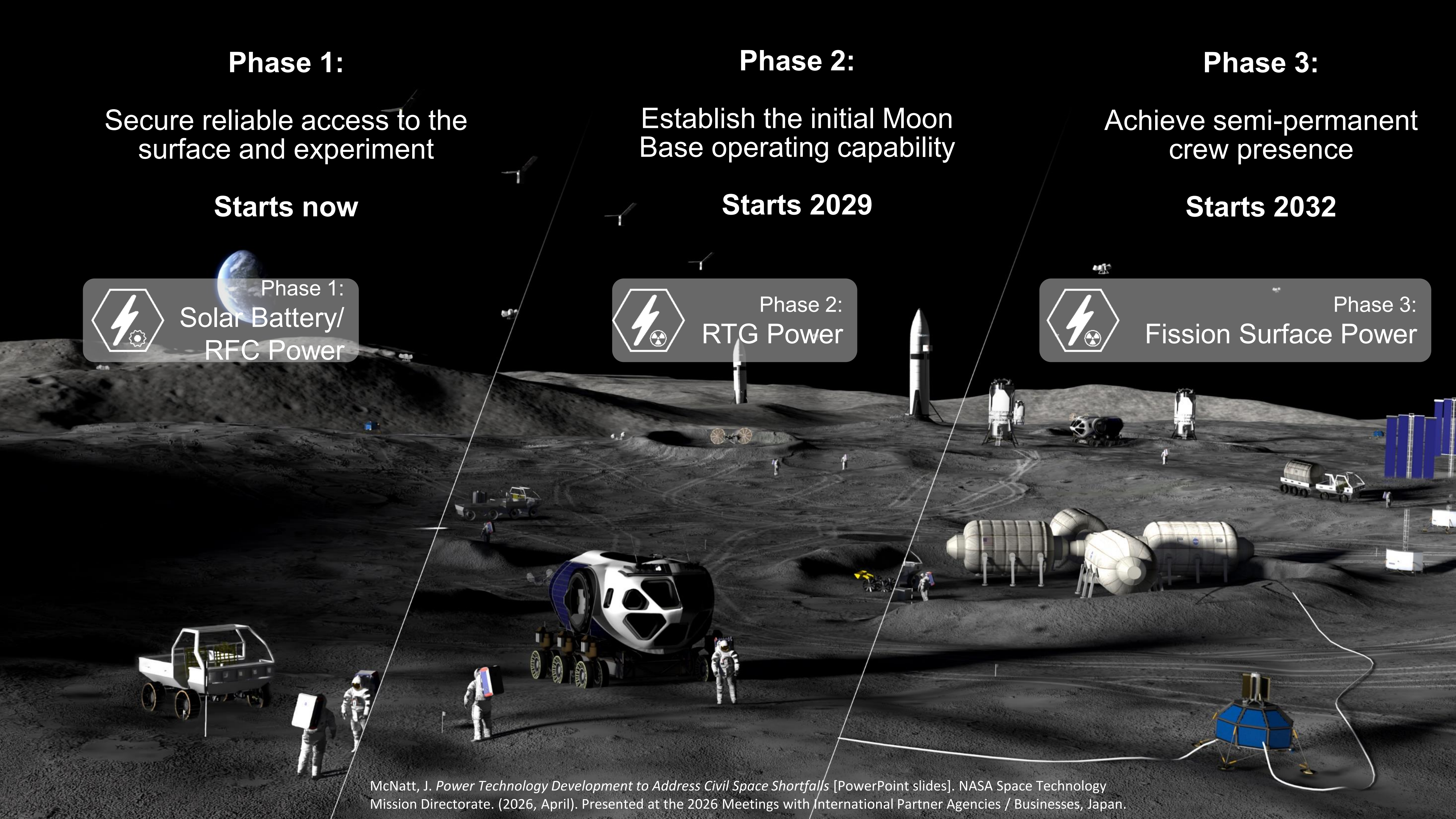
Establish the initial Moon Base operating capability

Starts 2029

Phase 3:

Achieve semi-permanent crew presence

Starts 2032



McNatt, J. *Power Technology Development to Address Civil Space Shortfalls* [PowerPoint slides]. NASA Space Technology Mission Directorate. (2026, April). Presented at the 2026 Meetings with International Partner Agencies / Businesses, Japan.

The Benefits and Challenges of Illumination

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

Lunar Equatorial Illumination Limits

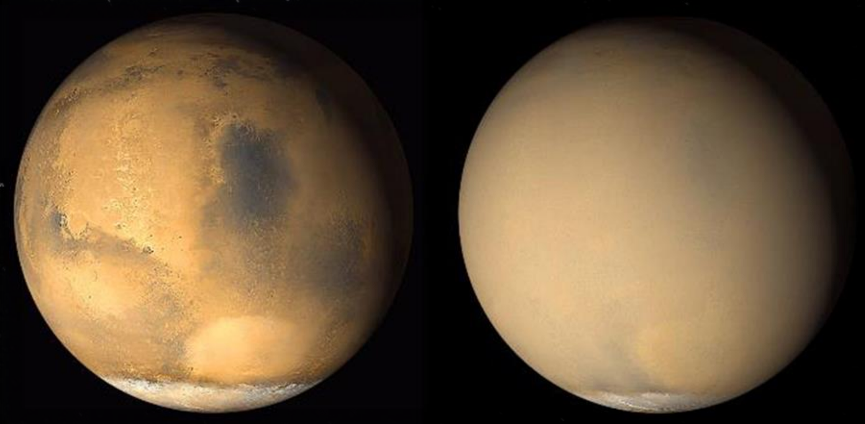
- Cyclical periods of 14 days illuminated, 14 days (*340 hours*) dark
- Consistent

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

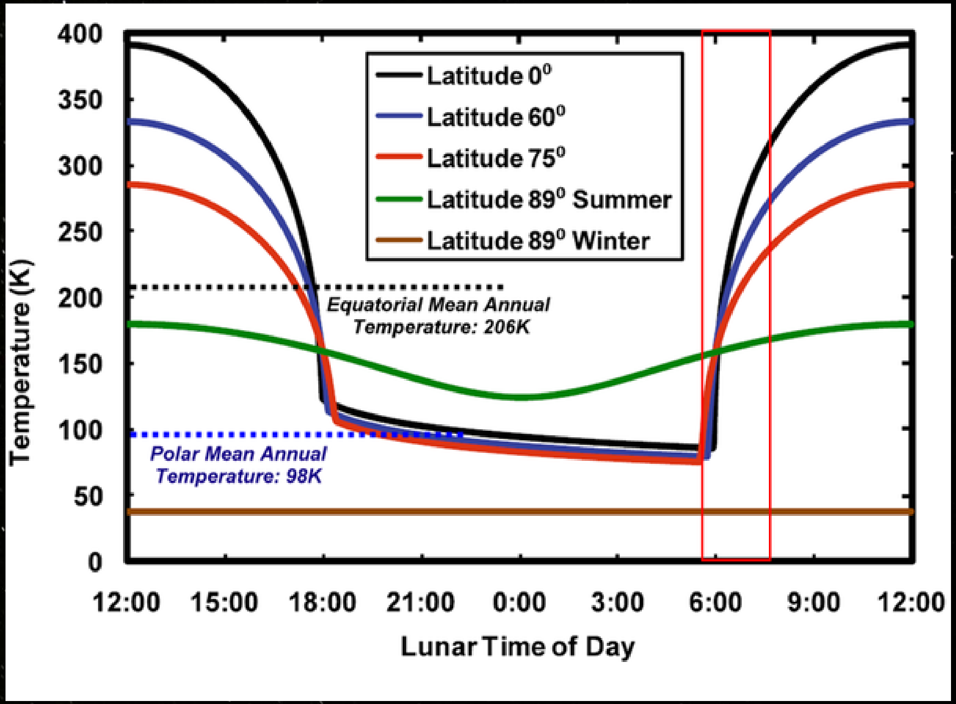
- Global and Local dust storms decrease illumination as much as 95% in extreme cases



McNatt, J. *Lunar Surface Power: Needs, Challenges, and Technologies* [PowerPoint slides]. NASA Space Technology Mission Directorate. (2026, February 10). Virtual presentation delivered to the Ohio Federal Research Network (OFRN) Opportunity Days.

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).



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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

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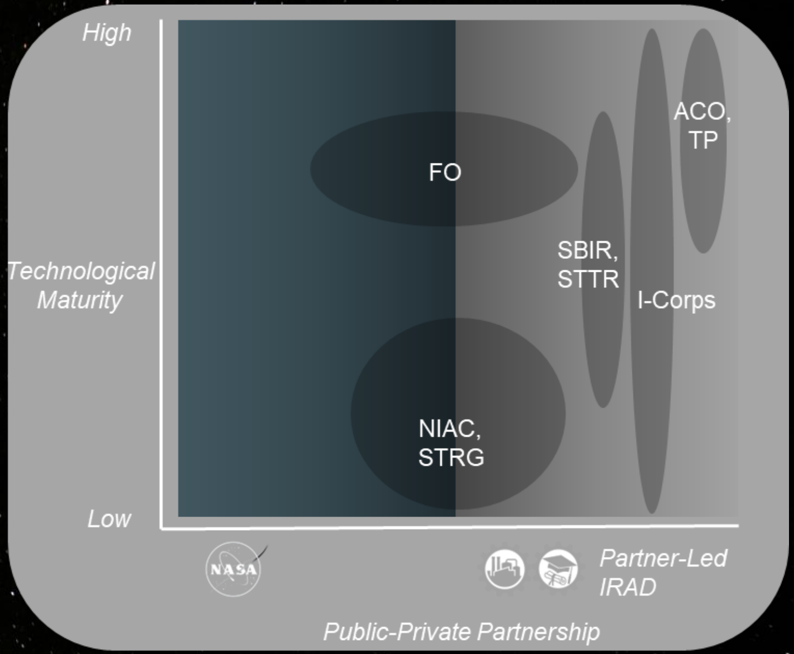
NASA's Innovation Pipeline

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.

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NASA Power Capability Facilities & Expertise Distribution

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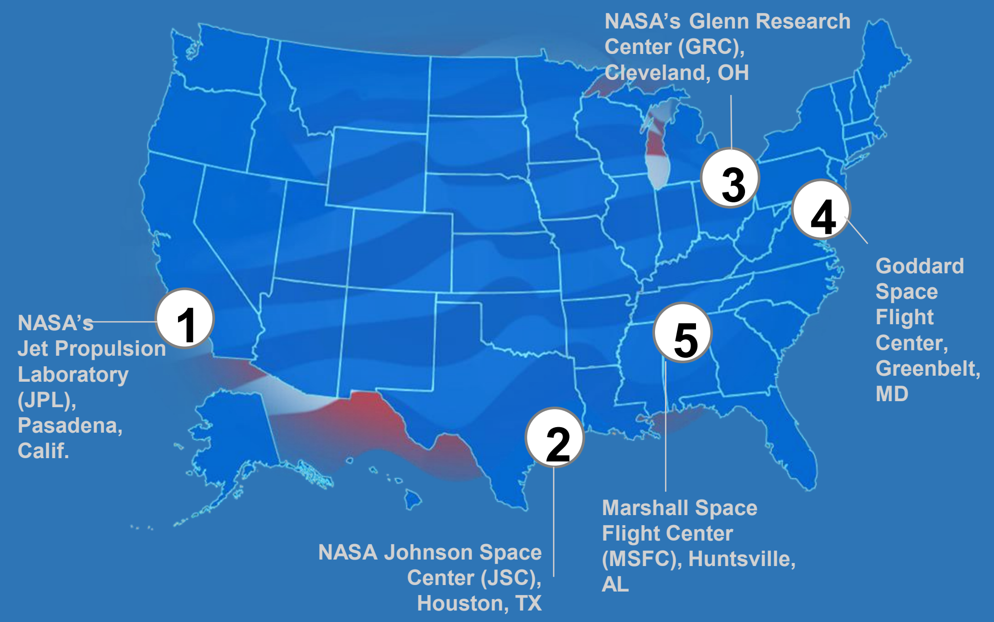


FACILITIES SERVING MULTIPLE POWER CAPABILITIES

- 3 GRC: Propulsion System Lab (TVAC Systems)
  GRC: Microgravity facilities
- 4 GSFC: TVAC Systems
- 1 JPL: TVAC Systems
- 2 JSC: TVAC Systems and Power hardware testing
- 5 MSFC: TVAC Systems
  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/

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

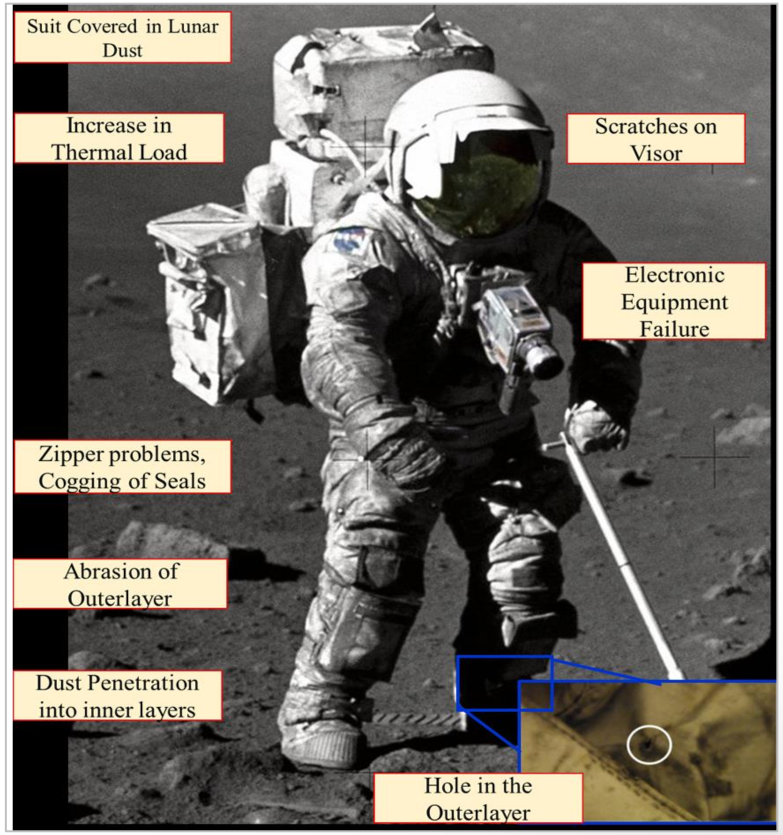
ENERGY STORAGE

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

Dust is Difficult



Lunar dust effects on spacesuits and operations during Apollo[1]

Mission	#EVAs[1]	EVA Hours[1] (HH:MM)
Apollo 11	1	2:32
Apollo 12	2	7:45
Apollo 14	2	9:22
Apollo 15	1*+3	18:34
Apollo 16	3	20:14
Apollo 17	3	22:03
Total Apollo	14+1*	79.5hr
Artemis IV+	4	32:00
Artemis VI+		24hr/week

* Apollo15: 33-min Stand-up EVA out top hatch of LEM, before 3 EVAs

Dust is difficult!

***Excerpts of few remarks on Lunar dust from Apollo astronauts during Apollo missions*[2]**

- **Apollo 17-Cernan**: *"Dust - I think probably one of the most aggravating, restricting facets of lunar surface exploration is the dust and its adherence to everything no matter what kind of material, whether it be skin, suit material, metal, no matter what it be and it's restrictive friction-like action to everything it gets on"….."I think dust is probably one of our greatest inhibitors to a nominal operation on the Moon. I think we can overcome other physiological or physical or mechanical problems except dust."*
- **Apollo 16 -Young** *"Dust is the number one concern in returning to the moon"*

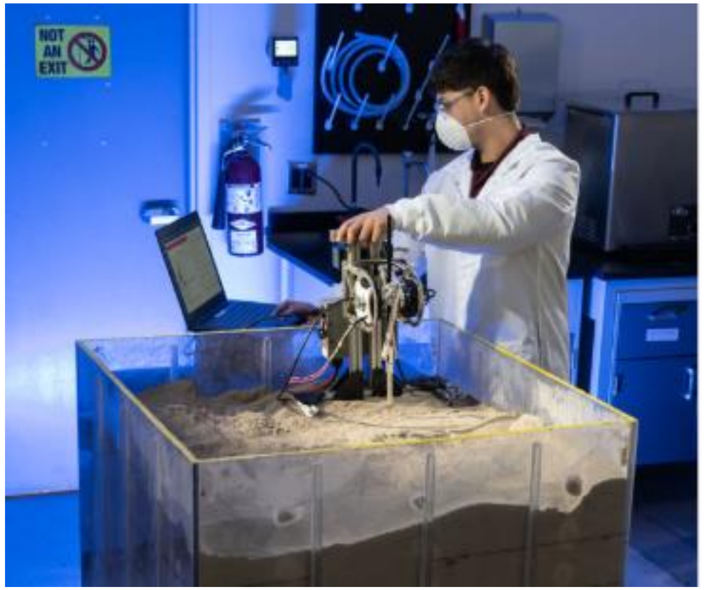
References:

1. Kavya K. Manyapu, Leora Peltz, Pablo De Leon, Self-cleaning spacesuits for future planetary missions using carbon nanotube technology, Acta Astronautica, Volume 157, 2019, Pages 134-144, ISSN 0094-5765, https://doi.org/10.1016/j.actaastro.2018.12.019
2. Gaier, J.R. (2005) The Effects of Lunar Dust on EVA Systems during the Apollo Missions, NASA/TM-2005-213610, NASA Glenn Research Center, Cleveland, Ohio. - References - Scientific Research Publishing. https://ntrs.nasa.gov/api/citations/20050160460/downloads/20050160460.pdf

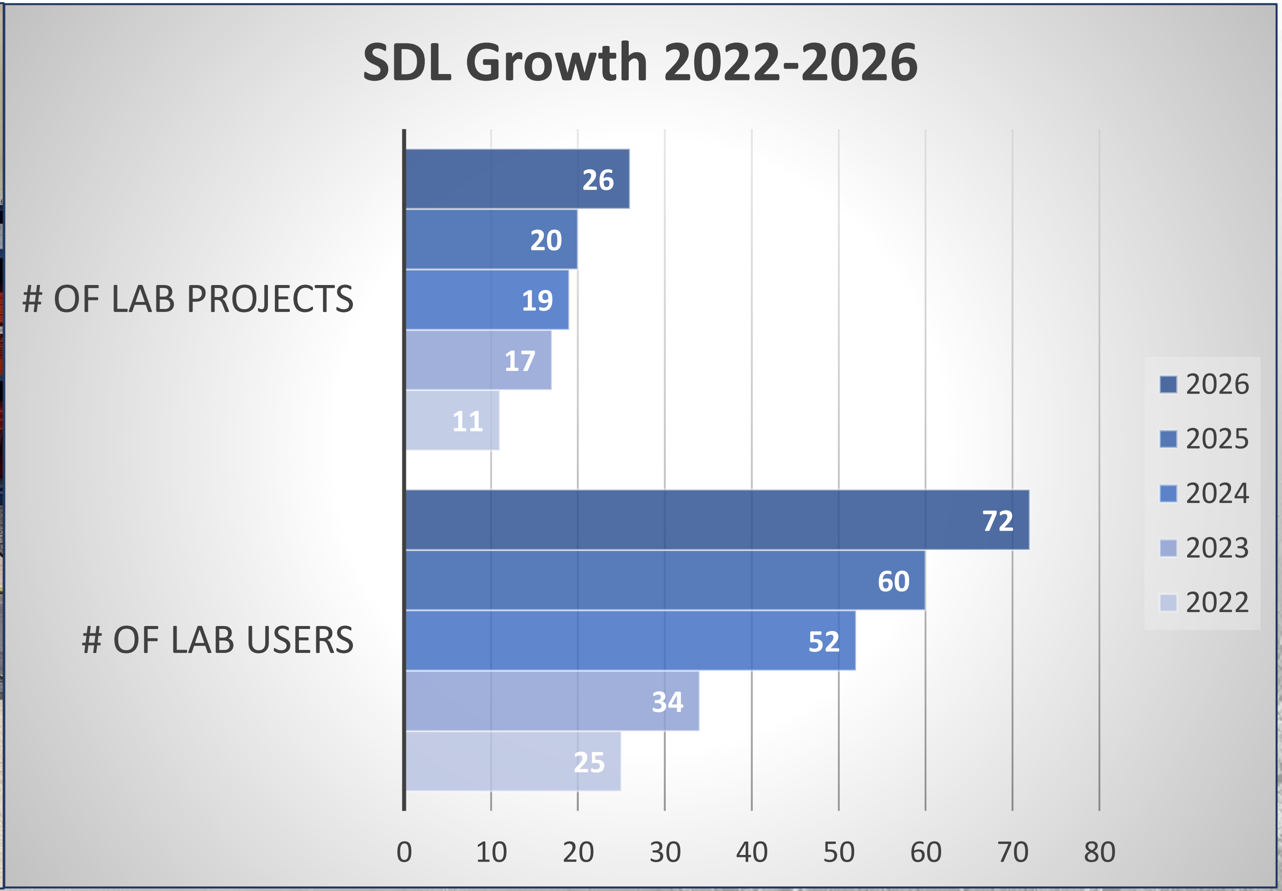
Simulant Development Lab (SDL) at JSC

- **Multifunctional collaborative lab space** that supports the **development**, **curation**, **analysis**, **testing**, and **distribution** of **planetary simulants** (Lunar, Martian, Asteroidal) and granular materials.
- Dynamic working space where **science** (*characterization of physical simulant properties*) and **engineering** (*tools, gloves and suit materials, dust mitigation, robotic prototypes*) **experiments can be conducted using testbeds with simulants**.
- The lab currently houses over ***35 metric tons of simulant material***.
- Houses a wide scope of **equipment and tools** used to **process simulants** (*including bulk simulant and feedstock materials such as rocks*) along with a key selection of **analytical instruments** which are used to **characterize** these materials.

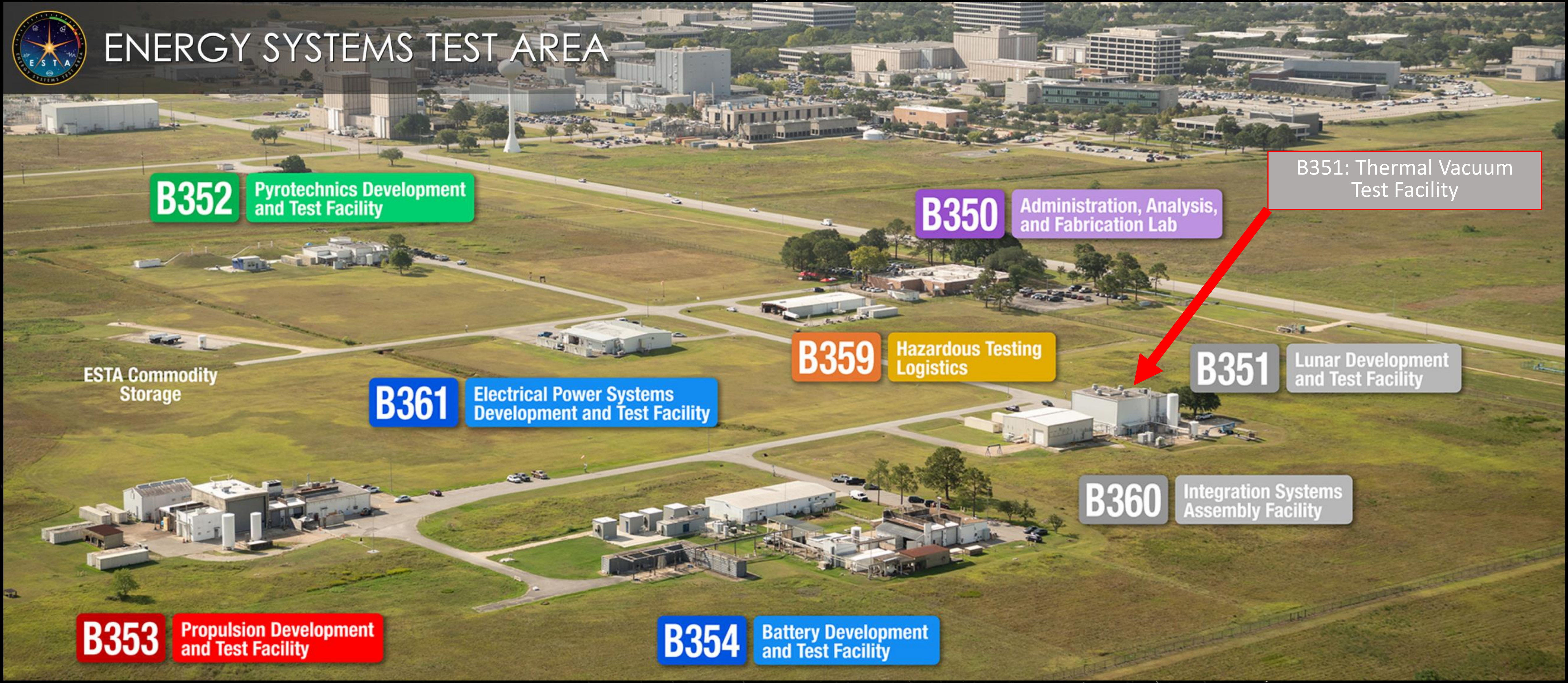




Simulant Development Lab (SDL) at JSC is growing



ESTA – Energy Systems Test Area at JSC



ESTA Dust Containment and Preparation Room

- Enclosed 750 ft^2 room sealed and equipped with HEPA fan filtration unit for dust containment and negative pressure maintenance.
- Particulate monitoring and audible alarm to ensure air quality is maintained.
- Provides room for regolith bin loading and preparation.
- Provides room for test article preparation and pre-conditioning prior to transfer to the 15’ chamber.
- Houses desktop ambient dust box and small vacuum bell jar.

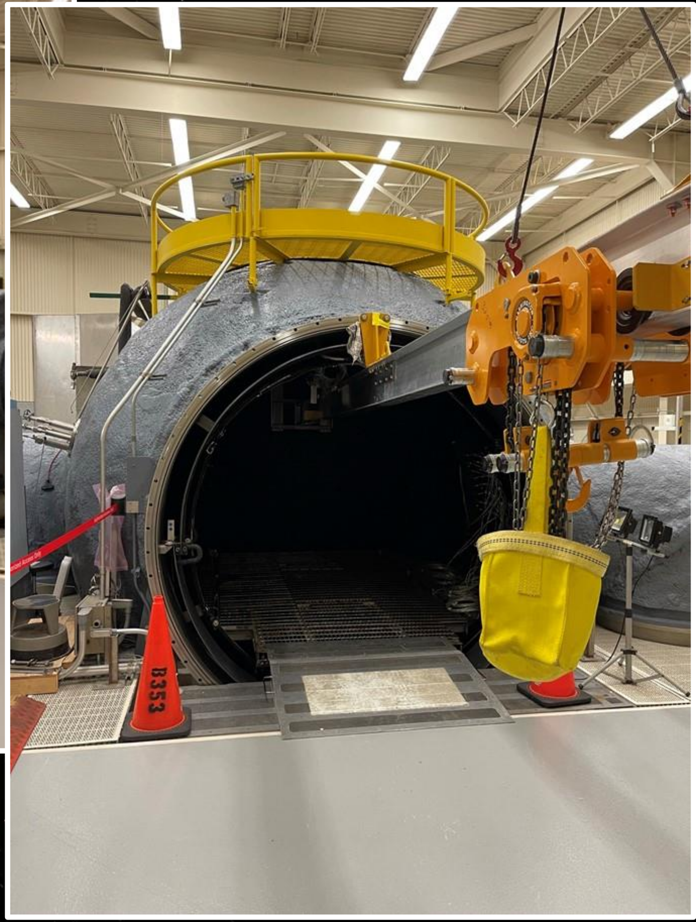
3ft Dusty TVAC Chamber

- Description
  - Dust tolerant 3’ TVAC chamber capable of testing components and technologies in lunar simulant
- Specifications
  - Dimensions: 36” x 36” x 36”
  - Vacuum: $1x10^{-6}$ torr
    - Throttleable roughing pump-down with Pfeiffer turbopump for high vacuum
    - $1x10^{-6}$ torr within 1-hour, empty chamber
  - Atmosphere: Air or GN_2 Repressurization
  - Thermal Range: -185°C to +150°C Thermal shroud temperatures
  - Shroud walls independently controlled for zone temperature conditioning if needed

15ft Dusty TVAC Chamber

15ft Dusty TVAC Chamber

- Description
  - 15ft Φ Spherical Chamber with ~78in Φ clear entry
  - Dust tolerant chamber capable of testing systems or subsystems with lunar simulant
- Environment Capability
  - Vacuum: $1x10^{-6}$ torr (ultimate),
    - Pumping, rotary piston pumps, roots blowers & two 36in diameter diffusion pumps
  - Atmosphere: Air or GN_2 Repressurization
  - Thermal Range: -196°C to +120°C Thermal shroud temperatures
  - High channel count data feedthroughs
  - High power feedthroughs available
  - Max platform load: 4,000 lb
  - Test article operation on 48" x 96" regolith bed in chamber with surface interactions with regolith to depths down to ~6 ft
- Previous tests: used for fuel cell, electric APU during Shuttle, Cryogenic propellant storage, Apollo lunar rover tire



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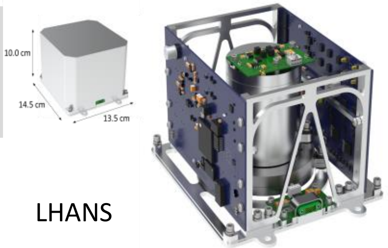
Example Science Instruments

Instrument	NASA M2M ADD Rev C Science Objective
Gamma-Ray Neutron Spectrometer (GNRS)	**LPS-3:** Understanding volatile composition and the environment of shallow permanently shadowed regions near the lunar South Pole **LPS-1, LPS-2:** Exploring the lunar South Pole region to understand chronology, composition, and structure of this region of the Moon **LI-7:** In Situ Resource Utilization (ISRU)
UV-VIS-NIR Spectrometer	**LPS-3:** Understanding volatile composition and the environment of shallow permanently shadowed regions near the lunar South Pole **LPS-1, LPS-2:** Exploring the lunar South Pole region to understand chronology, composition, and structure of this region of the Moon **LI-7:** In Situ Resource Utilization (ISRU)
Ground Penetrating Radar (GPR)	**LPS-3:** Understanding volatile composition and the environment of shallow permanently shadowed regions near the lunar South Pole **LPS-1, LPS-2:** Exploring the lunar South Pole region to understand chronology, composition, and structure of this region of the Moon **LI-7:** In Situ Resource Utilization (ISRU)
LIBS	**LPS-1, LPS-2:** Exploring the lunar South Pole region to understand chronology, composition, and structure of this region of the Moon
Neutral Mass Spectrometer (NMS)	**HS-1:** Space weather forecasting
Thermal Instrument (Imager)	**LPS-3:** Understanding volatile composition and the environment of shallow permanently shadowed regions near the lunar South Pole **LPS-1, LPS-2:** Exploring the lunar South Pole region to understand chronology, composition, and structure of this region of the Moon **LI-7:** In Situ Resource Utilization (ISRU)
Raman Spectrometer	**LPS-3:** Understanding volatile composition and the environment of shallow permanently shadowed regions near the lunar South Pole **LPS-1, LPS-2: E**xploring the lunar South Pole region to understand chronology, composition, and structure of this region of the Moon **LI-7:** In Situ Resource Utilization (ISRU)
Dust Microbalance	**HS-1:** Space weather forecasting

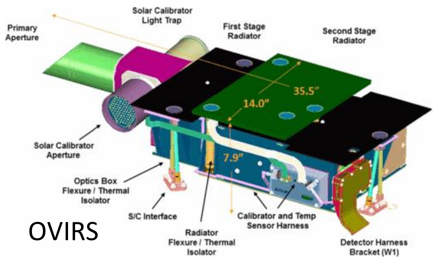
Turner, A. A., & Needham, D. H. (2026, April). Flown science instruments: Mass, size, and power characteristics [PowerPoint slides]. NASA.

Instrument	Mass (kg)	Volume (L)	Operating Power (W)	Average Power (W) during Cargo Transport	Mission Reference
Gamma-Ray Neutron Spectrometer (GNRS)	1.435 kg	2.0 L	7.2 W	7.2 W	**LHANS (LRM)**
UV-VIS-NIR Spectrometer	17.7 kg	58 L	14 W	3.4 W	**OVIRS (OSIRIS-REx)**
Ground Penetrating Radar (GPR)	1.6 kg	16 L	12 W	12 W	**WISDOM (Rosalind Franklin)**
LIBS	10.4 kg	20 L	18 W	4.5 W	**SuperCam (Perseverance)**
Neutral Mass Spectrometer (NMS)	11.3 kg	39 L	34 W	34 W	**NMS (LADEE)**
Thermal Instrument (Imager)	9 kg	18 L	13 W	3.3 W	**L-CIRiS (CLPS)**
Raman Spectrometer	10.4 kg	20 L	18 W	4.5 W	**SuperCam (Perseverance)**
Dust Microbalance	14.8 kg	11 L	20 W	20 W	**SUDA (Europa Clipper)**

Turner, A. A., & Needham, D. H. (2026, April). Flown science instruments: Mass, size, and power characteristics [PowerPoint slides]. NASA.

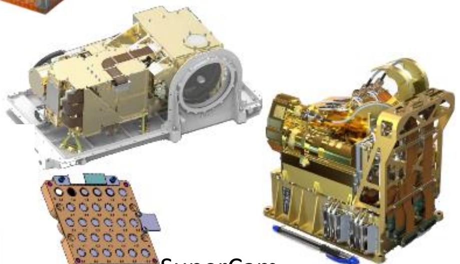


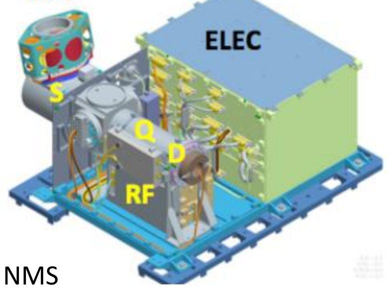
LHANS



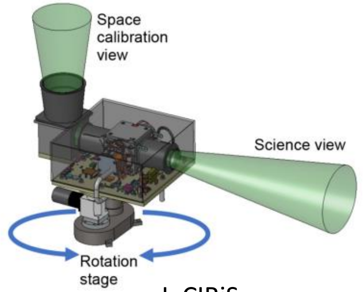
OVIRS


WISDOM

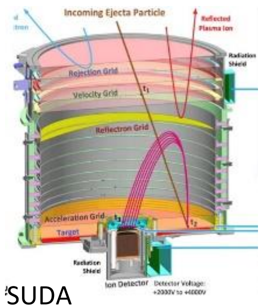

SuperCam



NMS



L-CIRiS



SUDA

Example Science Instruments continued

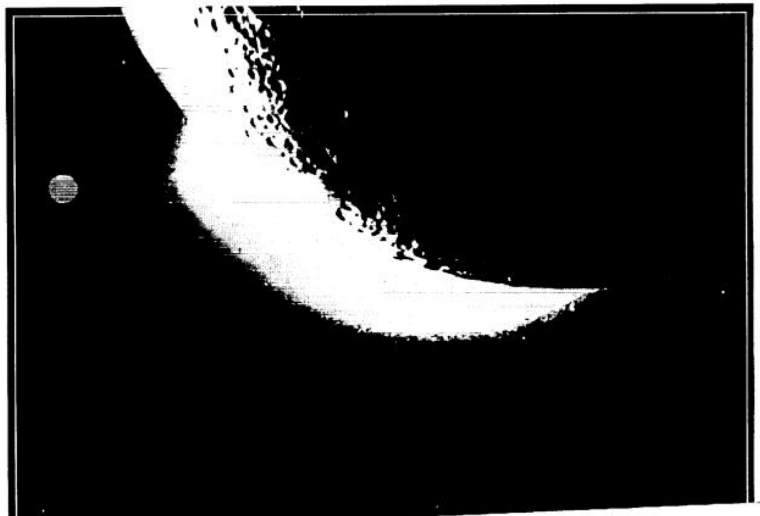
https://www.lpi.usra.edu/lunar/documents/NASA%20RP-1345.pdf

NASA Reference Publication 1345

IN-91
33177
236p

Catalog of Lunar and Mars Science Payloads

Nancy Ann Budden, Editor



(NASA-RP-1345) CATALOG OF LUNAR AND MARS SCIENCE PAYLOADS (NASA. Johnson Space Center) 236 p

N95-16436

Unclas

H1/91 0033199

August 1994

Power Consumption

Most equipment will not require any electrical power to operate. The following tools will require battery power:

Regolith drill	2150 W-hr @ 430 W
Rock drill	2000 W-hr @ 500 W
Multispectral imager	2000 W-hr @ 500 W

Power Consumption

Power will be supplied to each instrument after conditioning and distribution by the central station. ALSEP stations successfully used radioisotope thermal generators for power, although some form of advanced solar cell/battery technology may be available for this package. Because geophysical packages may be deployed in areas remote from a lunar outpost, the power source selected will have to be maintenance free and provide reliable power for a period of several years without human interaction. Conventional batteries are therefore unlikely to be used.

Planned power consumption on each instrument is as follows:

Central Station	25 W
Magnetometer	10 W
Passive Seismometer	10 W
Heat Flow Experiment	5 W
Ejecta and Meteorites Experiment	2 W
Discretionary PI Science	25 W

Power Consumption

Power will be supplied internally to each instrument by means of rechargable batteries. Instruments should be able to go at least 1 month of normal use between charge, which should allow the instrument package to be used on a long pressurized rover traverse without drawing off the internal power of the rover.

Preliminary estimates for power consumption on each instrument is as follows:

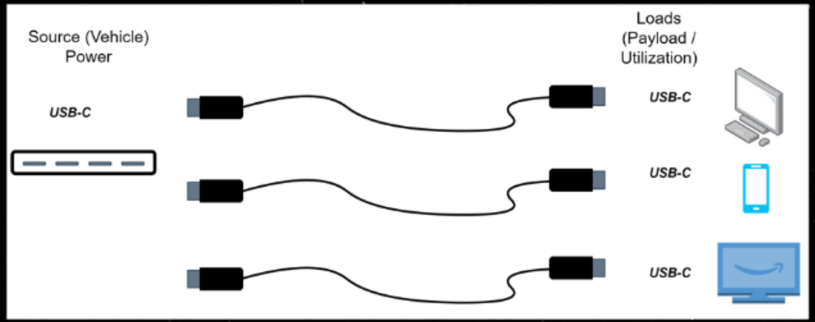
Electromagnetic Sounder	10 W
Active Seismic Experiment	10 W
Traverse Gravimeter	10 W
Electrical Properties Experiment	10 W
Profiling Magnetometer	10 W
Discretionary PI Science	25 W

Budden, N. A. (Ed.). (1994, August). Catalog of lunar and Mars science payloads (NASA Reference Publication 1345). National Aeronautics and Space Administration. https://www.lpi.usra.edu/lunar/documents/NASA%20RP-1345.pdf

USB Power Delivery over USB-C

Example of a current USB-C power strip

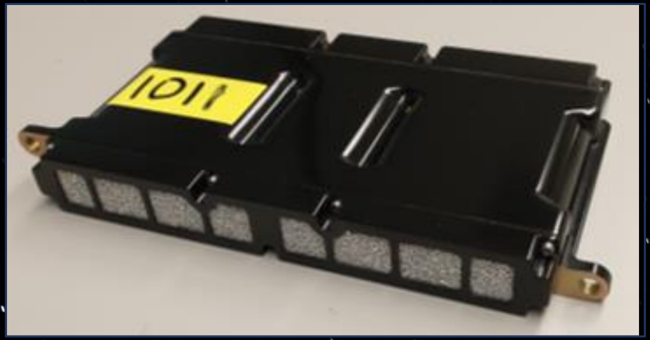
- **Purpose**: USB power delivery standard enables common interface and minimal unique cables, eliminating the need for discrete power conversion boxes
- **Description**: Works for various payloads, i.e. laptops, tablets, cameras, and/or medical equipment
- **Distinctive capabilities**: Compatible with any COTS USB-compatible hardware, no custom design required, LEO radiation-environment survivable
- **Potential users**: CLDP, LEO, Moon base, HLS, EHP
- **Technical Readiness Level**: 9 for 100 W source, 5-6 for higher power levels and charging



<table>
<tr><th colspan="3">Technical Parameters</th></tr>
<tr><td colspan="2">Input voltage: 120 VDC or 28 VDC</td><td>Size: 5” x 2” x 1”</td></tr>
<tr><td>Output power (TRL 9)</td><td>Output power (TRL 5-6)</td><td>Approximate time to deliver: Depends on radiation environment and criticality</td></tr>
<tr><td rowspan="2">• 15 W @ 3A, 5V
• 27 W @ 3A, 9V
• 45 W @ 3A, 15V
• 60 W @ 3A, 20V
• 100 W @ 5A, 20V</td><td rowspan="2">• 140 W @ 5A, 28V
• 180 W @ 5A, 26V
• 240 W @ 5A, 48V</td><td>Provides fixed power and battery charging</td></tr>
<tr><td>Working on EHP solution for HLS</td></tr>
<tr><td colspan="2">Mass: 2 lbm. (0.907 kg)</td><td>Unique vehicle power bus interfaces will necessitate a custom front-end design</td></tr>
</table>

Contact Martin Martinez (martin.d.martinez@nasa.gov) in EP5 for more information

Modular IVA/EVA Battery



- **Purpose**: Provide modular, safe storage and delivery of 95 Wh electrical power. Twelve modules provide 1 kWh stored energy
- **Description**: Designed for safe usage at all planned spacecraft environments, including those with smaller compartments and elevated O_2 levels
- **Distinctive capabilities**: Modular human-rated battery, addresses all battery safety ConOps
- **Potential users**: CLDP, LEO, Moon base, HLS, EHP, Mars forward
- **Technical Readiness Level:** 6-8, depending on spacecraft environment

Technical Parameters	
Energy/voltage: 95Wh at 0.5A, 86Wh at 11A, up to 24-32.8 VDC per module	Externally-replaceable fuse enables near-real time fault recovery
Size: 7.68“ x 0.90” x 3.99”	Usage Life: 5-15 years pending storage and usage conditions
Mass: 1.63 lbm (0.74 kg)	Can be connected in series or parallel for additional voltage ranges and or current carrying capacity
Chemistry: Lithium-Ion, 1P-8S, 18650 cell format	Can be configured to provide ~ 4, 8, 16, or 32V per module
Approximate time to deliver: ATP + 2-5 years, depending on cell design	Rack or external-strapped mounting configurations

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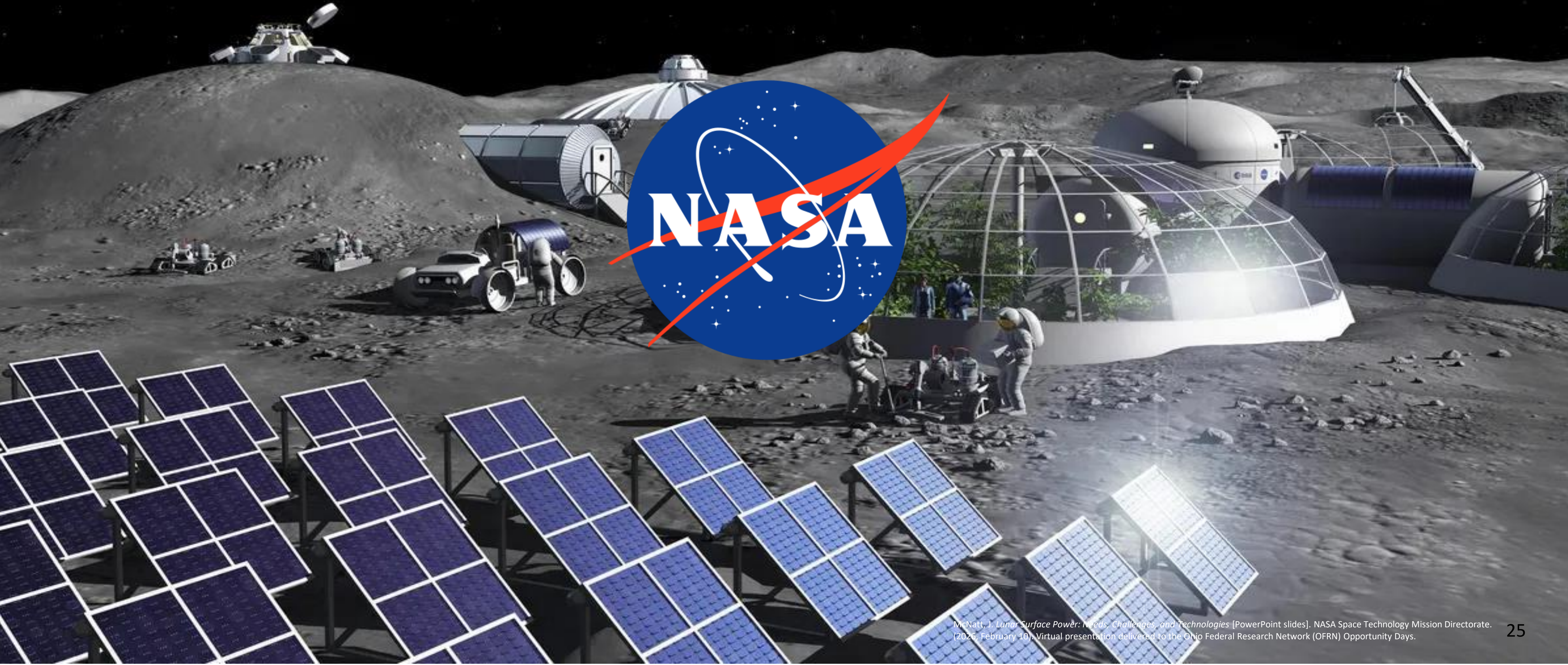
Thank You!



McNatt, J. *Lunar Surface Power: Needs, Challenges, and Technologies* [PowerPoint slides]. NASA Space Technology Mission Directorate. (2026, February 10). Virtual presentation delivered to the Ohio Federal Research Network (OFRN) Opportunity Days.