National Aeronautics and Space Administration

EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

Update on ISRU in NASA's Artemis Program

Progress from 2019 to 2025

Space Resources Roundtable
Golden, CO.

June 3, 2025

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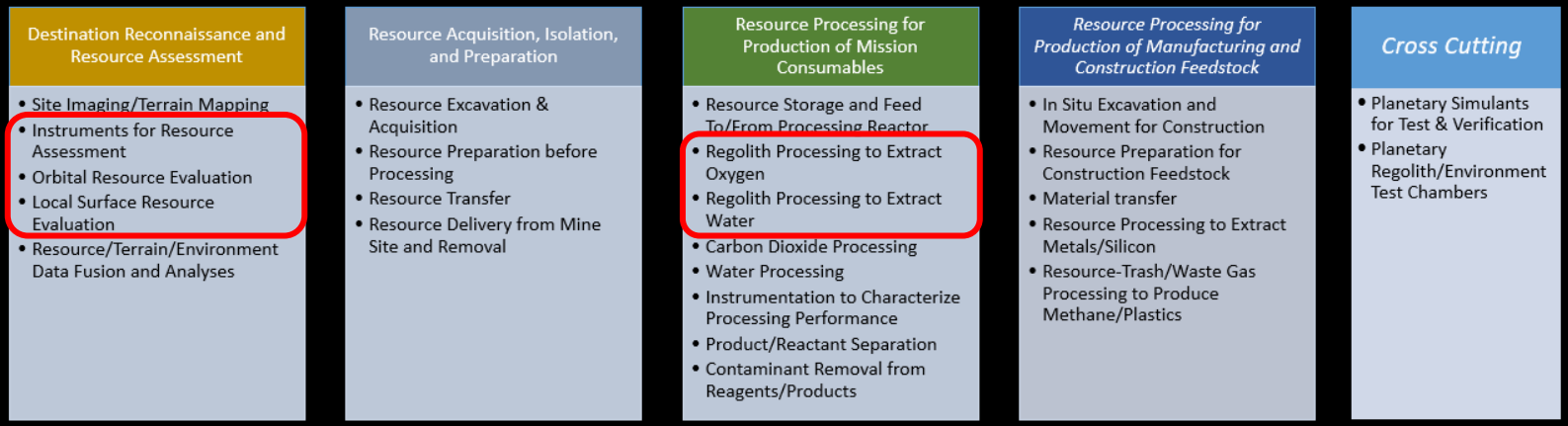
Plan to Achieve ISRU Outcome

*Goal: Scalable ISRU production/utilization capabilities including **sustainable commodities** on the lunar & Mars surface*

Enable Industry to Implement ISRU for Artemis, Sustained Human Presence, and Space Commercialization

Key Objectives

- **Market Transparency:**
  - Define Initial and Long-term Customer Needs for ISRU-derived Products
- **Technology & System Development:**
  - Identify and promote risks, challenges, and gaps; Eliminate Barriers for Commercial use of space resources
  - Utilizing NASA solicitations, public private partnerships, challenges, & internal/external investments
    - Build strong research and university involvement
    - Collaborate and partner with terrestrial resource exploration, mining, and processing; promote spin-in/spin-off
  - Promote extensive ground and low-g aircraft testing
- **Mission Insertion:**
  - Promote resource exploration and flight demonstrations to reduce risk and validate operations and products/commodities (non-mission critical/mission enhancing)
  - Promote investment and development in Industry-led ISRU thru End-to-End ISRU Production of Commodities (i.e. Pilot Plant) and usage
  - Promote collaborations with industry and international partners



Commodities

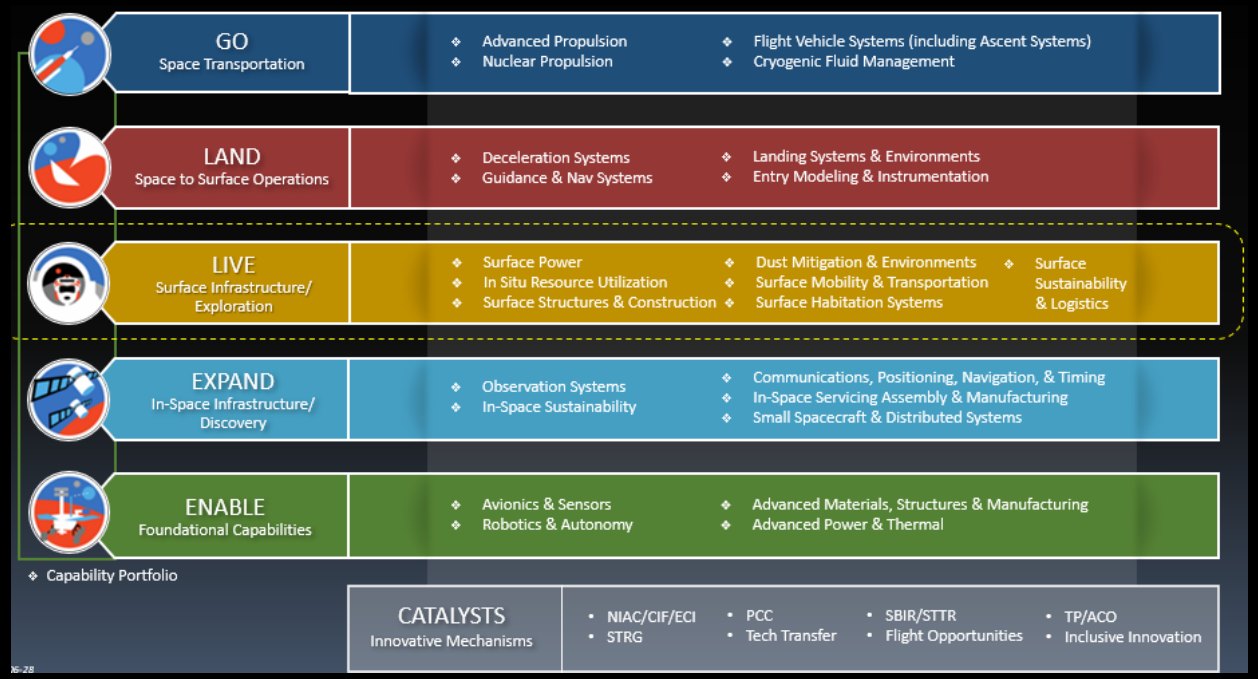
- **Oxygen**
- **Water - Hydrogen**
- **Bulk & Refined Regolith**
- **Raw & Refined Metals (Al, Fe, Ti)**
- **Silicon and Ceramics**
- **Construction Feedstock**
- **Manufacturing Feedstock**
- **Fuels, Plastics, Hydrocarbons**
- **Food/Nutrient Feedstock**

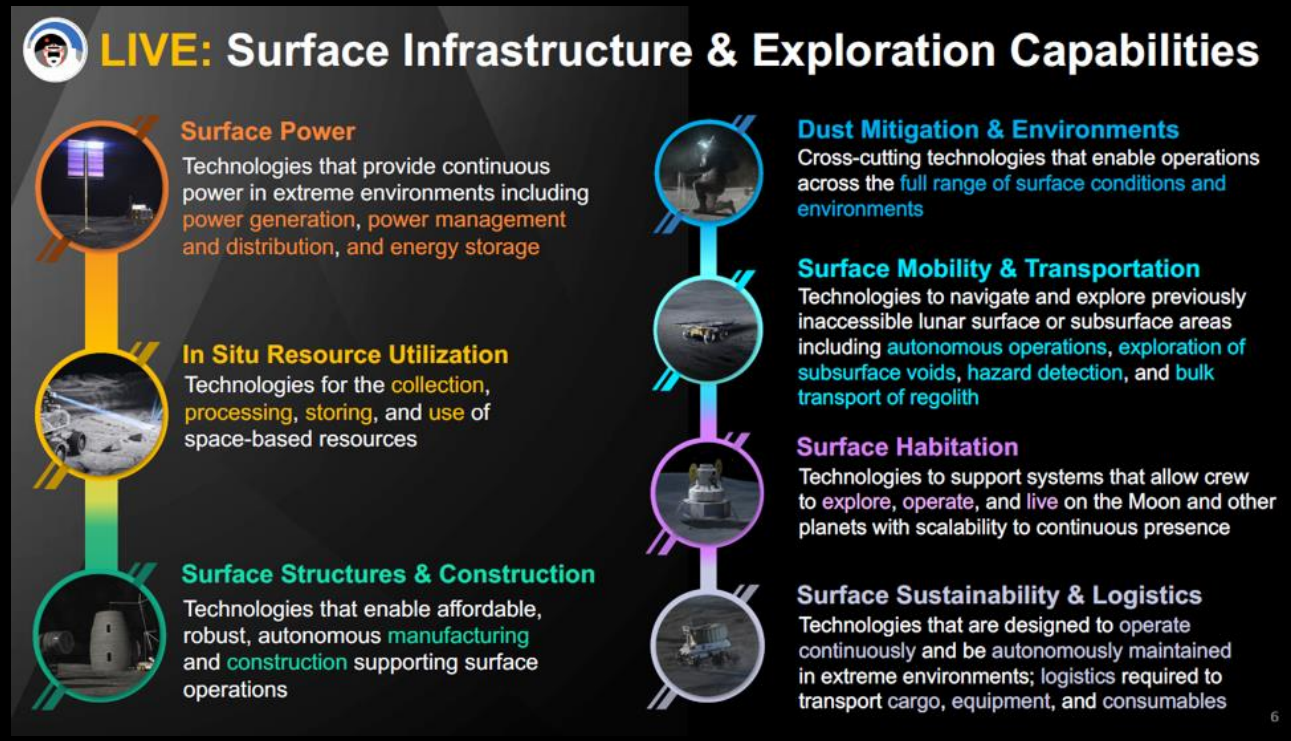
Reexamine STMD Approach to Developing Technologies & Systems (1 of 2)

STMD Focus on Ensuring American Global Leadership in Space Technology centered around **Technology Readiness Level (TRL)** based Solicitations

Reexamine STMD Approach to Developing Technologies & Systems (2 of 2)

Focus is now on Technology Base **Functional Domains**

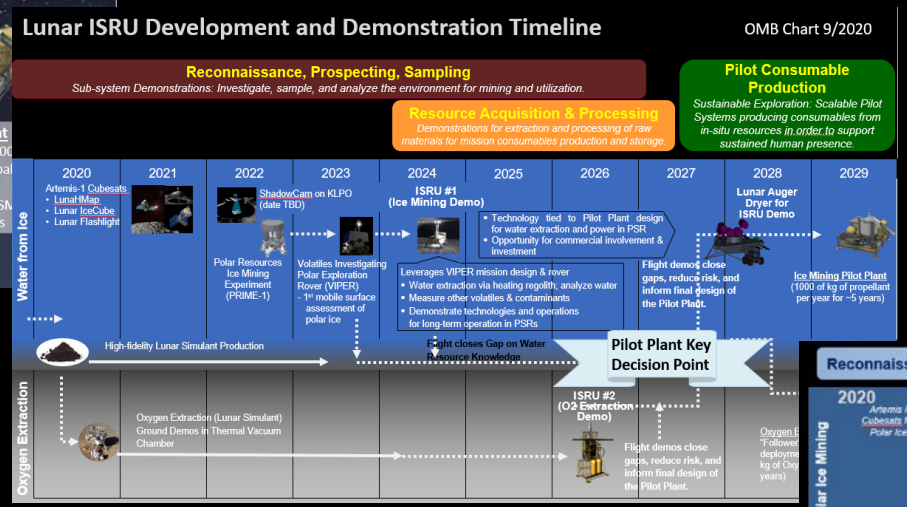




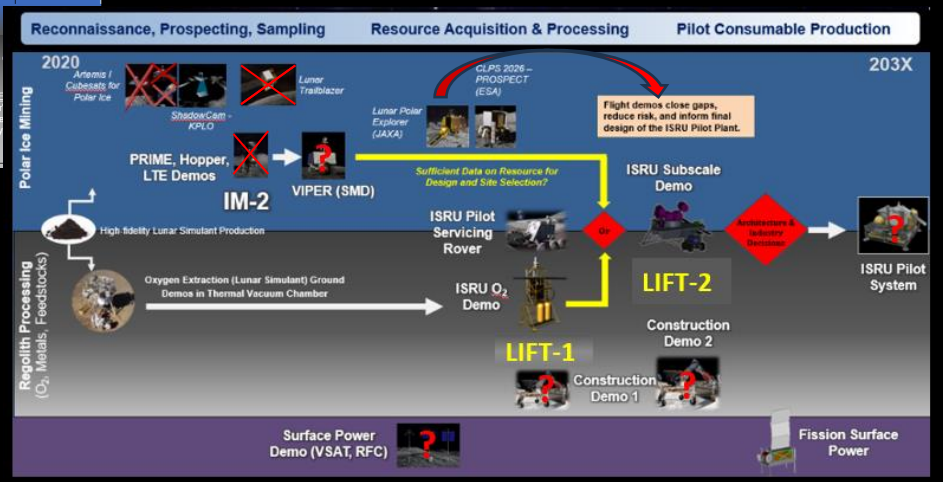
Solicitations will now support more focused **Capability Roadmaps** and **Priorities**

Evolution of STMD Lunar ISRU Development & Mission Plans

From the start, the Driving Strategy for ISRU in STMD was to try to Break the 'Chicken & Egg' cycle by Demonstrating ISRU Systems and Product at Relevant Mission Scale to eliminate the risk for Full-Scale Commercial Operations



The emphasis on Enabling Industry to be Successful has grown over time



However

Mission failures, cancellations, delays in Artemis missions, and budget cuts have forced a reevaluation of priorities, development approach, and flight implementation

STMD Rethinking Lunar Missions and Infrastructure Going Forward

Two charts presented at LSIC Spring Meeting point to a desire to establish lunar infrastructure, provide demand signals and infusion paths, and chart a path to evolve from **'Missions to Markets'**

What is Surface *Infrastructure*?

The definition of "infrastructure" is "the fundamental physical and organizational structures and facilities needed…to function effectively."

Establishing lunar surface infrastructure is the essential step to go from shorter-term Apollo-like missions to longer-term missions on the Moon and Mars; Simply put, it is **evolving from 'footprints to foundations'**

What does that translate to in terms of lunar infrastructure?

- **Today's novel technologies must become tomorrow's institutional capabilities** that can be scaled and infused into mainline missions (i.e. not a 'one-off')
- Capabilities can be **deployed, return to, and (re)used**
- **Assets become aggregated surface systems thus, establishing a U.S. presence** and bolstering commercial capabilities (i.e. utilities model, "pipes and roads.)

Surface Power Generation, Storage, & Distribution

Environments & Dust Mitigation

Autonomous & Robotic Systems

Sustainability & Logistics (e.g. Surface Mining, Excavation, & Construction)

[1]

Establishing Surface Infrastructure

The definition of "establish" is "to set up, create, or found something in a firm or stable way"

Emphatic feedback from the community has centered around **the need for NASA to chart a path for emerging Moon and Mars capabilities to evolve from 'missions to markets';** this theme is not only from the LSIC participants over ~five years, but also via tremendous response to the 2023 Lunar Infrastructure Foundational Technologies-1 (LIFT-1) RFI

- NASA needs to establish a national plan beyond isolated landings that provides a stable *demand signal and infusion path* for the burgeoning U.S. commercial ecosystem
- *Technologies and architecture* should culminate in a cohesive infrastructure that can be used and reused by future missions for a commercial lunar ecosystem and/or Mars extensibility
- Industry technologies matured via NASA awards and *partnerships with considerable commercial IRAD investments* should be inherently incorporated into the infrastructure

In direct response, NASA and APL are developing the framework for a **future RFP that leverages U.S. industry innovation to develop a mission-driven technology pipeline** for a cost-effective minimum viable lunar surface infrastructure with commercial lunar and/or Mars extensibility, including:

- Surface Power: Generation, Storage, and Distribution
- Environments & Dust: Surviving the night; active, passive, and operational dust mitigation
- Communications / Position, Navigation, Timing (C&PNT)
- Autonomous & Robotic Systems
- Sustainability & Logistics: Surface Mining/ISRU, Excavation, and Construction, Interoperability

[2]

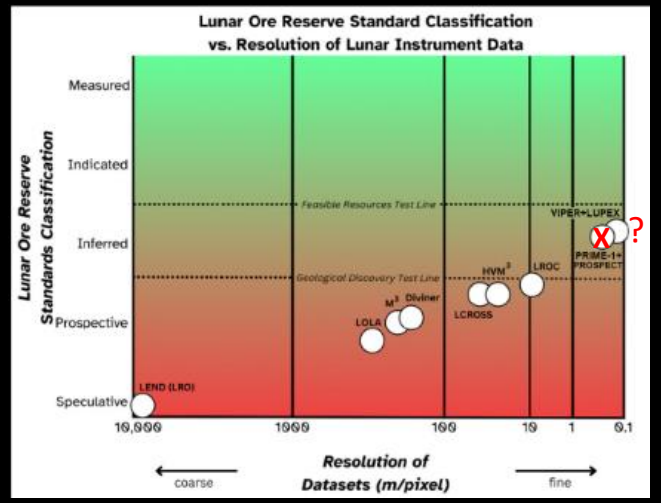
Resource Exploration for ISRU: Missions with Relevant Instruments & Rovers Have Already Started; Some have failed

	2022	2023	2024	2025	2026	2027	2028
Orbital	**- KPLO - ShadowCam (Korea)** ***- Lunar IceCube*** ***- Lunar Flashlight*** ***- LunaH-Map***	- Chandryaan-3 (India)		***- Lunar Trailblazer***		**- Luna-26 (Russia)**	
South Pole			*- IM-1 - Malapert A*	***- IM-2 - STMD-PRIME-1*** - Draper - Schrödinger Basin - Blue Moon Mark 1	**- CP26_Prospect (ESA)** **- Chang'e-7 (China)** **- VIPER?**	**- IM-4 - South Pole (ESA PROSPECT)**	**- Chang'e-8 (China)** **- LUPEX (JAXA/ISRO)?** **- Luna-27 (Russia)** - CLPS?
Equatorial		- Chandryaan-3 (India) *- ispace 1 (Japan)* *- Luna-25 (Russia)*	*- Astrobotic - Gruithusen Domes*	- Blue Ghost 1 - Mare Crissuml - ispace 2 (Japan) - Mare Frigoris - M-3 - Reiner Gamma	- Blue Ghost Mission 2 - Moon Far Side	- CPLS?	- CPLS?

Bold = Water/Ice Related mission *Red Italic* = Failed mission

- **A significant Number of Instruments and Rovers have been developed for Lunar Science that are applicable to Resource Assessment**
  - Some are already manifested
  - Not all are aimed at understanding lunar resources
- **Need to utilize existing instruments to the maximum extent possible before investing in new instrument capabilities**
  - New instruments should fill a gap and be directly tied to critical data needs or concepts of operation
  - No US instruments currently funded for icy regolith sample acquisition and heating
- **Need resiliency in measurements and missions**
  - Mission cancellations and failures can cause significant gaps in knowledge and cause delays
  - Multiple manifesting at different locations can also help advance confidence in geological context of measurements

Missions need to build-off of knowledge gained from previous missions to increase Reserve Estimation



**Patterson R, O'Brien H., Galien L., Vaenciano J., Neal C.R. (2024) Examining the Reserve Potential of Lunar Polar Volatiles. Space Resources Roundtable, Colorado School of Mines; 4-7 June 2024*

= Equatorial location
= Polar location
= Cancelled
Italics = International

	TO 2-AB Peregrine	TO-2 IM-1	TO19D Blue Ghost 1	TO19C Masten	IM-2 PRIME-1	VIPER Griffin	TO 20A Griffin	CP-11 IM-3	CP-12 Draper	CP-22 IM-4; *Prospect (ESA)*	CS-3/4 Blue Ghost 2	*Chandrayaan-3 (India)*	*SLIM (JAXA)*	*LUPEX (JAXA)*	*Luna 27 (Russia)*
Landing Location	E	E	E	P	P	P	P	E	P-F	P	E-F	P	E	P	P
Physical Properties/Sample Acquisition															
LISTER - Pneumatic Drill			X						X						
RAC - Regolith Adherence Characterization			X												
EDS - Electrodynamic Dust Shied			X												
LITMS - Magnetotelluric sounder + Heat Probe									X						
PlanetVac - Pneumatic Transfer			X												
SAMPLR - Arm scoop				X											
ColdARM - Arm scoop															
Trident - 1 m Auger Drill					X	X									
Drill - 1.5 m (JAXA)														X	
ProSEED Drill - 1 (ESA)										X					
Drill - 2 m (Russa)															X
Thermal Measurement (Russia)															X
CHaSTE - Surface thermal Conductivity & Temp												X			
Langmuir Probe												X			
High Res Surface Camera NIRVSS)						X									
Subsurface/Indirect Measurment															
NSS Neutron Spec	X			X		X									
NMLS Neutron Spec															
Puli Space NS					X										
LUPEX GPR														X	
CADRE GPR								X							
Farside Seismic Suite (FSS)									X						
FLEET passive seismometer (SPIDER)											X				
Lunar Magnetotelluric Sounder (LMS)			X												
Mineral Characterization															
NRVSS - Near IR Spec	X			X		X									
LUPEX NS														X	
L-CIRIS - Compact InfraRed Imaging Sensor										X					
XRD/XRF eXTraterrestrial Regolith Analyzer															
Ultra-Compact Imaging Spec - Shorwave IR															
BECA - Gamma Ray Speec w/ Pulsed Neurtons															
Mid IR														X	
IR, UV (Russia)															X
Gamma Ray Spec (Russia)															X
Multispectral microscope								X							
Multi-Band Camera													X		
APXS - AlphaParticle X-ray Spec												X			
LIBS - Laser Induced Breakdown Spec												X			
Volatile - Direct Measurement															
MSolo - Mass Spec					X	X									
PITMS - IonTrap Mass Spec	X														
CRATER - Laser-based Mass Spec															
NIRVSS - Near Infrared Spec				X		X									
Water Analyzer System (REIWA); TGA, Triple Reflection, Optical Resonance, Raman														X	
ProSPA: Ion Trap & Mag Sector MS, 6 LED Spec										X					
Sample Processing System: GC/MS and Laser MS															X
Large Rover w/ Payloads						X	X							X	
MicroRovers															
CubeRover							X								
MoonRanger w/ NSS				X											
MAPP rover - Lunar Outpost					X			X							
Micro Nova Hopper w/ NS					X										
CADRE Rovers (3) w/ GPR								X							
Pragyan rover (India)												X			
Hakuto rover (ispace)															
Lunar Excursion Vehicles 1 & 2													X		

Lunar ISRU - Oxygen from Regolith – Constellation 2006-2011

- **First comprehensive engineering effort to advance lunar ISRU**
  - Resource prospecting, regolith excavation, transfer, and processing
- **Oxygen from Regolith**
  - Low risk/low performance – Hydrogen (H_2) Reduction
  - Medium risk/medium performance – Carbothermal (CH_4) Reduction
  - High risk/high performance – Molten Regolith Electrolysis (MRE)
- **Started Search for Lunar Polar Water**
  - RESOLVE → This led to Lunar Prospector (2011-18) → VIPER (2019+)
- **First attempts to evaluate integrated ISRU systems and Concepts of Operation at Analog Sites**
  - 2008: H_2 Reduction @ Mauna Kea, HI
  - 2010: CH_4 Reduction @ Mauna Kea, HI
  - 2012: Lunar Polar Water Prospecting @ Mauna Kea, HI

TRL increase in ETDP	At Start	At End	Delta
System Level			
Lunar Volatile Characterization (RESOLVE)	1	5	4
H_2 Reduction of Regolith	2-3	5	2-3
CH_4 Reduction of Regolith	2-3	5	2-3
Molten Oxide Reduction of Regolith	2	3	1
Trash Processing for Water/Methane Production	2	2-3	0-1
Subsystem Level			
Regolith Transfer & Handling			
Regolith Transport Into/Out of Reactor	2	5	3
Beneficiation of Lunar Regolith	2-3	2-3	0-1
Size Sorting of Lunar Regolith	2-3	2-3	0-1
Oxygen Extraction From Regolith			
H_2 Reduction of Regolith Reactor	3	5	2
Gas/Water Separation & Cleanup	2	4-5	2-3
CH_4 Reduction of Regolith Reactor	3	5	2
CH_4 Reduction Methanation Reactor	3-4	4-5	1-2
MOE of Regolith Anode/Cathode	1-2	3-4	2-3
MOE of Regolith Molten Mat'l Removal	1-2	3	1-2
MOE Cell and Valving	2-3	3	0-1
Water/Fuel from Trash Processing			
Trash Processing Reactor	2	2-3	0-1
In-Situ Energy Generation, Storage, and Transfer			
Solar Thermal Energy for Regolith Reduction	2	5	3

Hydrogen (H_2) Reduction - 2008

CH_4 Reduction - 2010

2008 2010 2012

RESOLVE (NASA – CSA)

Lunar Oxygen & Metals from Regolith – Results to Date

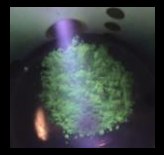
- **NASA invested in 8 different oxygen/metal extraction techniques based on NASA and industry assessments**

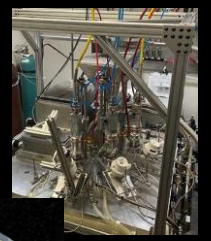
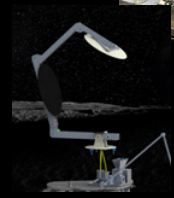
- **Highest TRL Oxygen Extraction from Regolith technology is Carbothermal Reduction**
  - Breadboard system tested in Hawaii in 2010 with mare-like material demonstrating technology and concept of operation
  - New prototype Carbothermal reactor built and tested with highland simulants through Tipping Point with Sierra Space
  - Breadboard and prototype reactors tested under lunar environmental conditions with laser at JSC to TRL 5
    - Single melts demonstrated that are equivalent to a production rate of 140 kg O_2/yr.
    - 5 consecutive melt operations were performed under lunar vacuum/thermal conditions
    - Oxygen extraction demonstrated >20 g O_2/kW-hr thermal; O_2 production yield of >20% gm O_2 per gm regolith; >99.7% recovery of the carbon used in melt.
  - Integrated Reactor/Solar concentrator system to be tested in 2025 through collaboration between NASA & Sierra Space

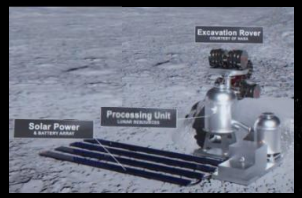
- **Molten Regolith Electrolysis (MRE) TRL has significantly improved for Oxygen and Metal Extraction (Fe, Si, Al)**
  - Lunar Resources - MRE iron reactor tested under lunar environmental conditions (at KSC) in single melt/electrolysis operation to demonstrate oxygen production under lunar conditions – TRL 5
    - 25 kg of lunar highland simulant was processed over 36 hours (24 hrs of electrolysis) and measured oxygen production rate matched theoretical levels
    - Separate but linked Iron, Si, and Al reactors all in work; Advancing concept of 'immortal' plasma electrode
  - Blue Origin - MRE and purification reactors (Fe, Si, & Al) under development along with solar cell and aluminum wire fabrication subsystems
    - Advancing modules to enable earlier cislunar commercial applications (metals, oxygen, silicon wafers, solar cells)
    - Integrated system lunar environmental testing to be completed in mid 2026
    - Collaboration with JSC to implement commercial scale propellant-grade oxygen capture system
    - Demonstrated and delivered to TRL 4/5: MRE Fe and Si cells, Al wire, oxygen capture system, and solar cell production

- **Technologies for lunar operations also have interest for terrestrial applications & clean iron/steel (and vice versa)**
- **Technologies are advancing with Industry IR&D and/or venture capital funding**

Lunar Oxygen & Metals from Regolith** - Reactors





Thermochemical Reduction/Oxidation Methods

- Hydrogen Reduction
- Carbothermal Reduction (CO_2, CH_4, C)
- Carbochlorination (CO, Cl_2)
- Hydrogen Sulfide Reduction
- Fluorine Exchange

Plasma Hydrogen Reduction Process (KSC) – TRL 2/3

MMOST (H_2/CO – mare) (Pioneer Astronautics) – TRL 4/5

Carbothermal Reduction Reactor *(Sierra Space) – TRL 4/5*

Carbothermal Reduction System (JSC) – TRL 4/5

Reactive Solvent Methods

- Hydrofluoric Acid Leach
- Hydrochloric Acid Leach
- Sulfuric Acid Reduction
- NaOH Reduction
- Ionic Liquid Reduction

Lunar Forge - HCl & MSE of Anorthosite (Missouri S&T) – TRL 3/4

Alkaline Al from Waste Slag (Pioneer Astronautics) – TRL 3

Ionic Liquid Reduction of O_2 & Metals (MSFC) – TRL 2/3

Ionic Liquid Reduction of O_2 & Metals (Faraday Tech) – TRL 2/3

Ionic Liquid Reduction of O_2 & Metals (Diatomic Space) – TRL 2/3

Ionic Liquid Reduction of Regolith (UC Boulder) – TRL 2/3

Electrochemical Methods

- Lithium Metal Reduction
- Aluminum Reduction
- Molten Salt Reduction (MSE)
- Molten Regolith Electrolysis (MRE)

Molten Regolith Electrolysis Start & Reactor (KSC & Lunar Resources)– TRL 4/5

MRE – Fe Reactor *(Lunar Resources) – TRL 4/5*

MRE Silicon/Iron *(Lunar Resources) – TRL 3/4*

MRE Immortal Anode (Lunar Resources) – TRL 3

MRE – Iron, Silicon, Aluminum Reactors *(Blue Origin) – TRL 4*

Domed MRE (Ethos Space) – TRL 3/4

Pyrolytic Methods

- Vapor Phase Reduction: Recovery by Distillation
- Vapor Phase Reduction: Electrostatic/magnetic
- Vapor Phase Reduction: O_2 via Solid Oxide

Multi-stage O_2 & Regolith Extractor (Blueshift)

Carbothermal/Vapor Pyrolysis with Solar Concentrator (Blueshift)

High Purity O_2 Separation from Pyrolysis Gas (A-Terra)

Vapor Pyrolysis (Terraxis) - TRL 2/3

**Barbara Altenberg, "Processing Lunar In-Situ Resources", Final Report, Technical Research and Development Project Job No. 90634-002, Bechtel Group, Dec. 1990

**Italics = Some or all non-NASA funding*

Lunar Polar Ice/Water Mining – Results to Date

- **NASA invested in 3 different water mining approaches: excavation with open/closed reactors, subsurface containment, and subsurface heating**

- **Excavation & Delivery**
  - Loose Regolith Excavation and Delivery demonstrated to TRL 5 in simulated mission
    - Arm/scoops and mobile excavators (Bucket drum, Bucket wheel, and Bucket ladder) developed and demonstrated
    - ISRU Pilot Excavator (IPEx) bucket drum excavator demonstrated in simulated mission (10 mt in 5 days)
  - Hard Icy Regolith Excavation and Delivery demonstrated to TRL 5 in simulated excavation and delivery – Break the Ice Challenge
    - 15 Teams: 15 days of ops at developers' site; Excavate 12,000 kg (800 kg/day). Each delivery = 500 m traverse
    - 6 Teams: 2 days of competition at Alabama A&M (timed performance)

- **Icy Regolith Processing**
  - Icy Regolith Processing Reactor Subsystem demonstrated to TRL 4 – Lunar Auger Dryer ISRU (LADI)
    - Continuous processing with regolith plugs at each end; Aimed at goal of 1.78 kg/hr water extraction rate and 75% water extraction efficiency (1 run accomplished at 0.53 kg/hr water extraction rate with >99% extraction eff.)
    - Cancelled before progressing to TRL 5 due to budget cuts but technology/concept validated
  - Contained Subsurface Material Reactor/Core demonstrated to TRL 5/6 – Planetary Volatile Extractor (PVEx)
    - Coring drill contains icy regolith. Inner core wall is heated (via electrical or thermal fluid) and water/volatiles sublimate and are captured in a coldtrap
    - Initial design was 1 meter core w/ 2.5 cm inner diameter. Large IDs examined. Performance contingent on icy regolith properties and core diameter & length; (5 cm ID, 0.5 m L, 4 to 6 wt% water, 43 to 56% water extraction)
  - Subsurface Heating & Surface Capture demonstrated to TRL 2/3
    - Results to date have not been promising; near surface desiccation, low thermal conductivity of regolith, icy regolith simulant density, and surrounding lower temperature regolith inhibiting liberation to surface collection

- **Final designs will be based on icy regolith resource information not currently available**

Lunar Polar Water/Volatile Mining and Processing

- **Three Primary Methods for Extracting/Mining Water on the Moon**

Excavation w/ Processing Reactor

- Closed Reactor/Auger
- Open Reactor

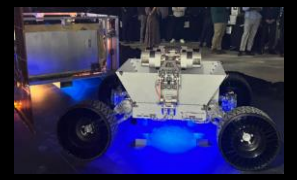
Lunar ISRU Auger Dryer (JSC) – TRL 4

Aqua Factorum (UCF) – TRL 2/3

*Column Dryer (Starpath) – TRL 3/4**

*Solar heated Dryer (Argo Space) – TRL 4**

Open Dryer Reactor (GRC) – TRL 3



Contained Excavation/Subsurface Material

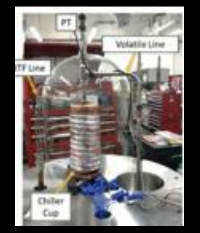
- Coring Drill
- Contained Excavation

Planetary Volatile Excavator – PVEx
(Honeybee Robotics) – TRL 5/6

Corer w/ Adv Heating (Adv Cooling Tech) – TRL 4

Lunar Water Extraction System (TransAstra) – TRL 2/3

PVEx



Corer w/
Adv. Heating

Subsurface Heating with Surface Collection/Dome

- Microwave/RF Heating
- Thermal Probes
- Surface Solar Heating

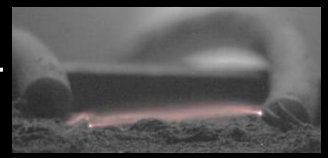
Lunar Polar Propellant Mining (TransAstra) – TRL 3/4

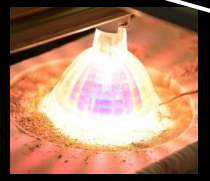
Lunar Water Extraction System (TransAstra) – TRL 2/3

Ablative Arch Mining (UT El Paso) – TRL 2/3

Advanced Thermal Mining (UT El Paso) – TRL 3/4

Thermal Lunar Mining (CSM) – TRL 2/3





**Italics = Some or all non-NASA funding*

Summation

- **A significant amount of development has occurred over the last 6 years since the start of the Artemis program wrt understanding, extracting, and processing lunar resources into usable products**
  - Industry is interested in commercial operations and is investing in technology development and flight opportunities
  - Flight demonstrations can proceed with reasonable risk for oxygen/metal extraction from regolith
  - Lunar water/volatile extraction is lacking sufficient resource knowledge to proceed without significant risk

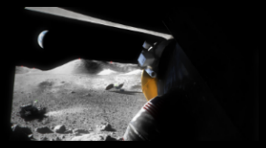
- **Next Steps ????? (*My Opinion*)**
  - Need to advance lunar integrated system development and testing; Foster partnerships for systems
  - Need knowledge of lunar polar ice form, concentration, distribution, etc. to mature technologies and systems.
  - Need to restart Mars ISRU development and better definition of water resources on Mars
  - Need to break the 'Chicken and Egg' problem with space resource use
    - Promote terrestrial and lunar proving grounds/commercial park
    - Provide incentives for space resource product usage

- **Artemis Needs To Be More Than Just About Science. *'It's the Economy Stupid!'***

BACKUP

Evolution of Moon to Mars Objective Decomposition for ISRU

Artemis Architecture Segments



HUMAN LUNAR RETURN
Initial capabilities, systems, and operations necessary to reestablish human presence and initial utilization (e.g., science) on and around the Moon.

FOUNDATIONAL EXPLORATION
Expansion of lunar capabilities, systems, and operations supporting complex orbital and surface missions to conduct utilization (e.g., science) and Mars-forward precursor missions.

SUSTAINED LUNAR EVOLUTION
Enabling capabilities, systems, and operations to support regional and global utilization (e.g., science), economic opportunity, and a steady cadence of human presence on and around the Moon.

Demonstrate & Utilize ISRU

HUMANS TO MARS
Initial capabilities, systems, and operations necessary to establish human presence and initial utilization (e.g., science) on Mars and continued exploration.

NASA Moon to Mars (M2M) Blueprint Objectives – ISRU Relevant

Resource Assessment	
AS-3[LM]	**Characterize accessible lunar and Martian resources,** gather scientific research data, and analyze **potential reserves** to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.
OP-3[LM]	**Characterize accessible resources,** gather scientific research data, and analyze **potential reserves** to satisfy science and technology objectives and enable use of resources on successive missions.
LPS-3[LM]	Reveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, **and sequestration of lunar and martian volatiles.**
TH-7[M]	Develop systems for crew to explore, operate, and live on the martian surface to address key questions with respect to science and **resources.**
SE-3[LM]	Develop the capability to **retrieve core samples of frozen volatiles** from permanently shadowed regions on the Moon and volatile-bearing sites on Mars and to deliver them in pristine states to modern curation facilities on Earth.

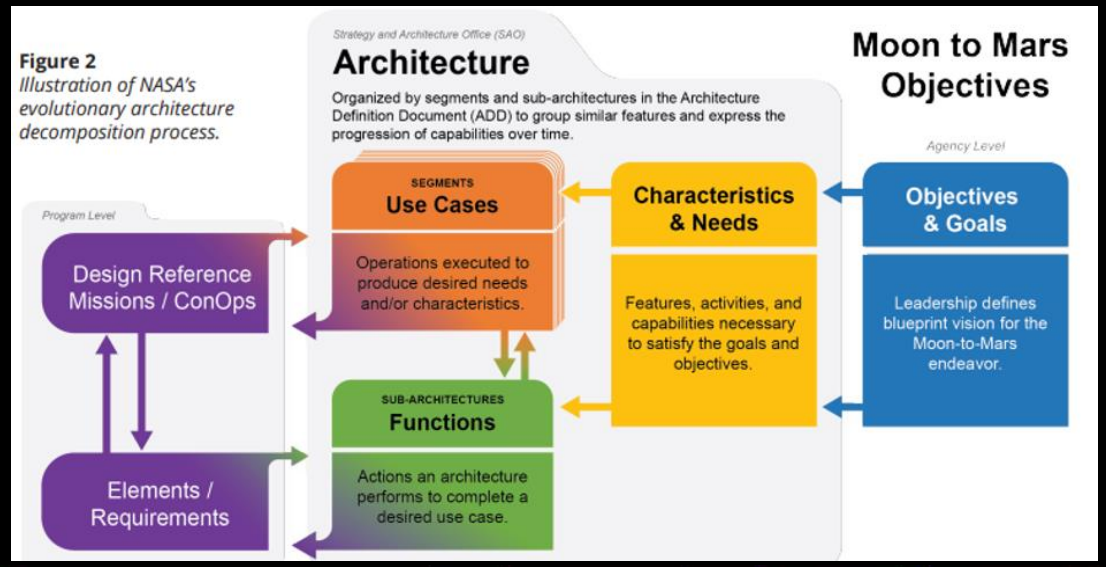
ISRU and Usage	
LI-7[L]	Demonstrate **industrial scale ISRU** capabilities in support of continuous human lunar presence and a robust lunar economy.
LI-8[L]	Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing **maximizing the use of in-situ resources,** and support systems needed for continuous human/robotic presence.
MI-4[M]	Demonstrate **Mars ISRU capabilities** to support an initial human Mars exploration campaign.
OP-11[LM]	Demonstrate the **capability to use commodities** produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.
TH-3[L]	Develop system(s) to allow crew to explore, operate, and live on the lunar surface and in lunar orbit **with scalability to continuous presence;** conducting scientific and industrial utilization as well as Mars analog activities.

Responsible ISRU	
SE-7[ML]	Preserve and protect representative features of special interest, including lunar permanently shadowed regions and the radio quiet far side as well as Martian recurring slope lineae, to enable future high-priority science investigations.
OP-12[LM]	Establish procedures and systems that will minimize the disturbance to the local environment, **maximize the resources available to future explorers, and allow for reuse/recycling of material transported from Earth** (and from the lunar surface in the case of Mars) to be used during exploration
LI-8[L]	**Develop** environmental monitoring, situational awareness, and early warning capabilities to support a resilient, continuous human/robotic lunar presence.
RT-6	**Responsible Use:** conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for responsible behavior in space

These are the Recurring Tenets; themes common across all blueprint objectives.	
RT-1	**International Collaboration:** partner with international community to achieve common goals and objectives
RT-2	**Industry Collaboration:** partner with U.S. industry to achieve common goals and objectives
RT-3	**Crew Return:** return crews safely to Earth while mitigating adverse impacts to crew health
RT-4	**Crew Time:** maximize crew time available for science and engineering activities within planned mission durations
RT-5	**Maintainability and Reuse:** when practical, design systems for maintainability, reuse, and/or recycling to support the long-term sustainability of operations and increase Earth independence
RT-6	**Responsible Use:** conduct all activities for the exploration and use of outer space for peaceful purposes consistent with international obligations, and principles for responsible behavior in space
RT-7	**Interoperability:** enable interoperability and commonality (technical, operations and process standards) among systems, elements, and crews throughout the campaign
RT-8	**Leverage Low Earth Orbit:** leverage infrastructure in Low Earth Orbit to support M2M activities
RT-9	**Commerce and Space Development:** foster the expansion of the economic sphere beyond Earth orbit to support U.S. industry and innovation

= Science: Lunar/Planetary Science (LPS), Science-Enabling (SE), Applied Science (AS)
= Infrastructure: Lunar Infrastructure (LI), Mars Infrastructure (MI)
= Transportation and Habitation (TH)
= Operations (OP)
= Recurring Tenets (RT)
= Key ISRU M2M Objectives

Artemis Architecture Definition Document, Rev. B



Functions		Use Cases		Characteristics/Needs		Objectives	
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	FN-T-202 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of ISRU on the lunar surface with long-term remote operation	UC-I-101 L	Deploy scalable demonstration ISRU exploration asset(s) on the lunar surface.	CH-I-101 L[M]	Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.	LI-07 L
Provide power for deployed external surface utilization payload(s) and/or equipment for long durations (months to years+)	FN-P-402 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	FN-M-402 L						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	FN-M-503 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Conduct ISRU utilization payload and/or equipment operations on the lunar surface	FN-I-104 L						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	FN-U-103 L						
Transport a moderate amount of cargo (1000s of kg) from Earth to south pole region sites on the lunar surface	FN-T-202 L	Deployment and operation of utilization payload(s) and/or equipment related to demonstration of oxygen recovery from lunar regolith	UC-I-102 L	Operate demonstration exploration asset(s) on the lunar surface to collect, produce, store, and transfer commodities, including water, oxygen, and/or construction feedstock, for potential use.	CH-I-102 L[M]		
Provide power for deployed surface utilization payload(s) and/or equipment	FN-P-401 L						
Enable crew lunar surface extravehicular activity in sunlit areas and non-PSRs	FN-M-101 L						
Unload a moderate amount of cargo (1000s of kg) on the lunar surface	FN-M-402 L						
Reposition a moderate amount of cargo (1000s of kg) at the south pole region on the lunar surface	FN-M-503 L						
Provide communications and data exchange between the lunar surface and Earth	FN-C-101 L						
Produce scalable quantities of oxygen from lunar regolith	FN-I-102 L						
Store oxygen on the lunar surface	FN-I-105 L						
Transport scalable quantities of oxygen produced to exploration elements	FN-I-107 L						
Collect regolith at sub-scale to support demonstration using scalable capability	FN-I-201 L						
Provide storage for collected regolith	FN-I-203 L						
Conduct resource identification utilization payload and/or equipment operations on the lunar surface	FN-U-103 L						

- Note: Decomposition currently only for Human Lunar Return (HLR) and Foundational Exploration (FE) Segments

Lunar Polar Water/Volatile Mining and Processing

▪ Icy Regolith Excavation

Granular
- Arm/Scoops
- Bucket Drum

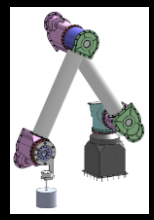
ColdARM (JPL) – TRL 5

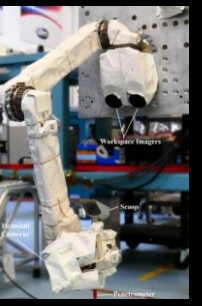
LUnA – Lunar Under-actuated robotic Arm (Maxar) – TRL 4

SAMPLR (Maxar) – TRL 6

MEERCAT Scoop/Size Sorter (KSC) – TRL 4

FLEET Utrasonic Blade/Bucket (GRC) – TRL 4





ISRU Pilot Excavator (KSC) – TRL 5

Excavation w/ min. volatile sublimation (Cislune) – TRL 2/3

Terrestrial Mining Technologies for Lunar Excavation (Offworld) – TRL 2/3

Consolidated/Hard
- Chisel
- Bucket Ladder
- Bucket Drum
- Bucket Wheel
- Ripper

Low Reaction Chisel Bucket (Singularity Solutions) – TRL 3/4

Lunar Ice Mining Using a Heat-Assisted Cutting Tool (Sierra Lobo) – TRL 3

Break the Ice Lunar Challenge *– TRL 4/5*
- Colorado School of Mines/Lunar Outpost
- Terra Engineering (1st Place Phase 2 AA&M; 2nd Place Phase 2)
- Starpath (2nd Place Phase 2 AA&M; 1st Place Phase 2)
- Cislune
- South Dakota State Univ
- MTU (3rd Place Phase 2 AA&M; Runner Up Phase 2)

Excavation Characterization (Research)

FLEET Excavation Force Determination (GRC)

Effects of Gravity on Soil Fluidization by Ultrasonic Probe (GRC)

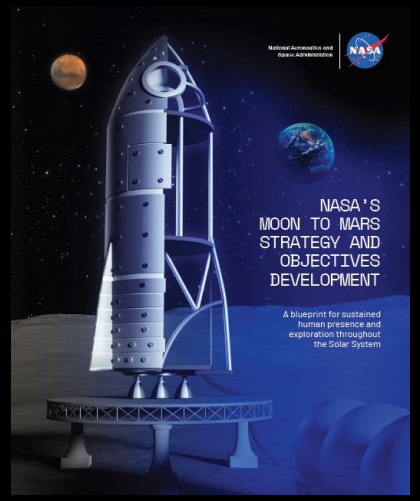
Ground Contact Force Characterization Rig (GRC)

Quantitative Optimization of Planetary Excavation Methods (UCF)

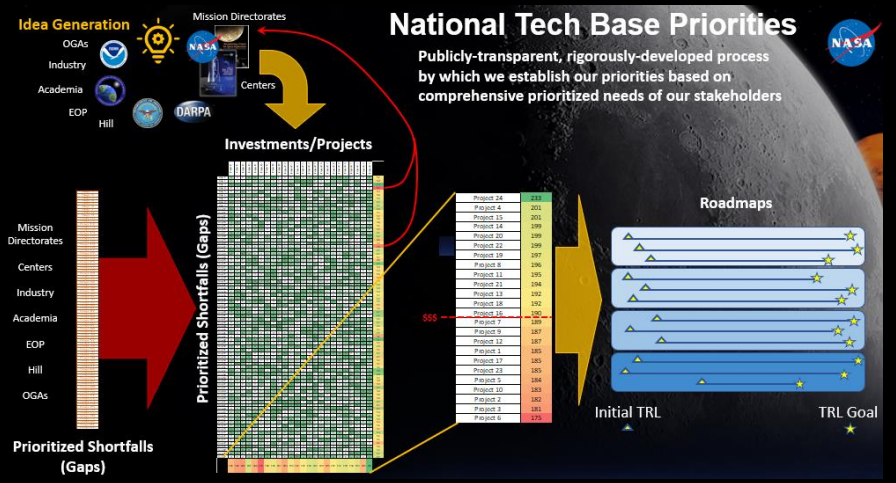
**Italics = Some or all non-NASA funding*

Growth In Community Input and Involvement in ISRU

Official Requests for Inputs on Objectives and Priorities



- Science
- Transportation and Habitation
- Infrastructure
- Operations
- Recurring Tenants



- Shortfall/Technology Priorities

Consortiums to Promote Industry - Commercialization

Lunar Surface Innovation Consortium

- ISRU, Surface Construction, Power, & Cross Cutting Focus Groups
- Bi-yearly LSIC Meetings
- Monthly Forums

COSMIC
CONSORTIUM FOR SPACE MOBILITY AND ISAM CAPABILITIES

- Standards
- Interfaces
- Interoperability
- Maintainability

LEAG
LUNAR • EXPLORATION • ANALYSIS • GROUP

Commercial Advisory Board (CAB)

LOGIC
LUNAR OPERATING GUIDELINES FOR INFRASTRUCTURE CONSORTIUM

Industry Interest and Investment

Public-Private Partnerships*

- Tipping Points/ACOs
- NASA Centers are encouraged to partner

Private Investment*

Enable Industry to Implement ISRU for Artemis, Sustained Human Presence, and Space Commercialization

A growing number of companies are receiving private investment to advance space resource utilization

*Organizations and Companies shown are not meant to be a full and exhaustive list