Moon to Mars In Situ Resource Utilization (ISRU) Status Update

International Cooperation Networking for Moon to Mars Resource Exploration and In-Situ Resource Utilization

Incheon, South Korea

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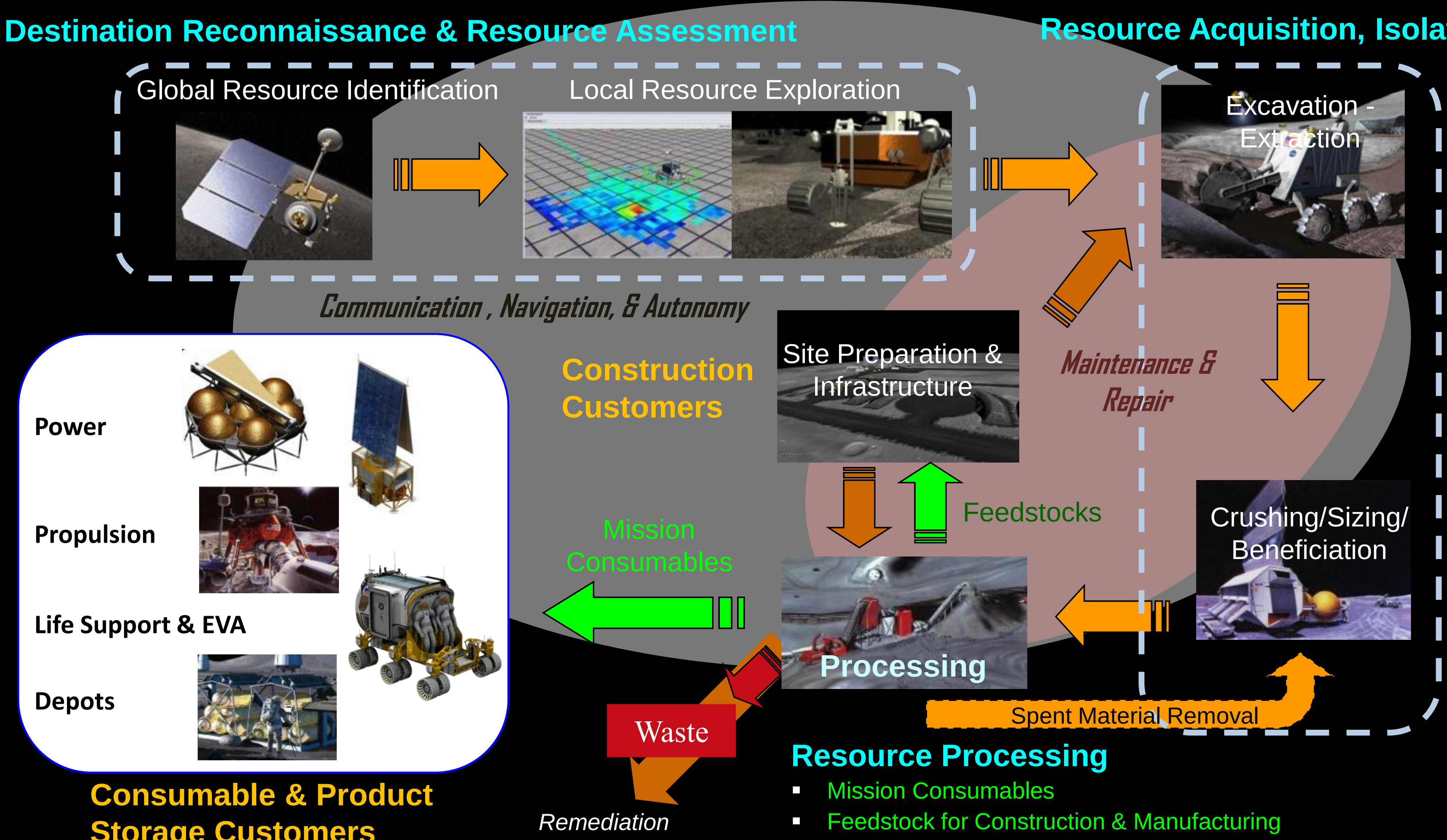
Presentation Content

- What is ISRU and Lunar Interests?
- How Does ISRU Fit Into Plans for Artemis?
- How Will ISRU Be Developed and Demonstrated?

What is In Situ Resource Utilization (ISRU) and Lunar Interests?

Lunar In Situ Resource Utilization *'Prospect to Product'* Mining Cycle

ISRU involves any hardware or operation that harnesses and utilizes 'in-situ' resources to create commodities* for robotic and human exploration and space commercialization



- **ISRU is a capability involving multiple disciplines and elements to achieve final products**
- **ISRU does not exist on its own. It must link to users/customers of ISRU products**

ISRU Functional Breakdown And Flow Diagram

Destination Reconnaissance and Resource Assessment

- Site Imaging/Terrain Mapping
- Instruments for Resource Assessment
- Orbital Resource Evaluation
- Local Surface Resource Evaluation
- Resource/Terrain/Environment Data Fusion and Analyses

Resource Acquisition, Isolation, and Preparation

- Resource Excavation & Acquisition
- Resource Preparation before Processing
- Resource Transfer
- Resource Delivery from Mine Site and Removal

Resource Processing for Production of Mission Consumables

- Resource Storage and Feed To/From Processing Reactor
- Regolith Processing to Extract Oxygen
- Regolith Processing to Extract Water
- Carbon Dioxide Processing
- Water Processing
- Instrumentation to Characterize Processing Performance
- Product/Reactant Separation
- Contaminant Removal from Reagents/Products

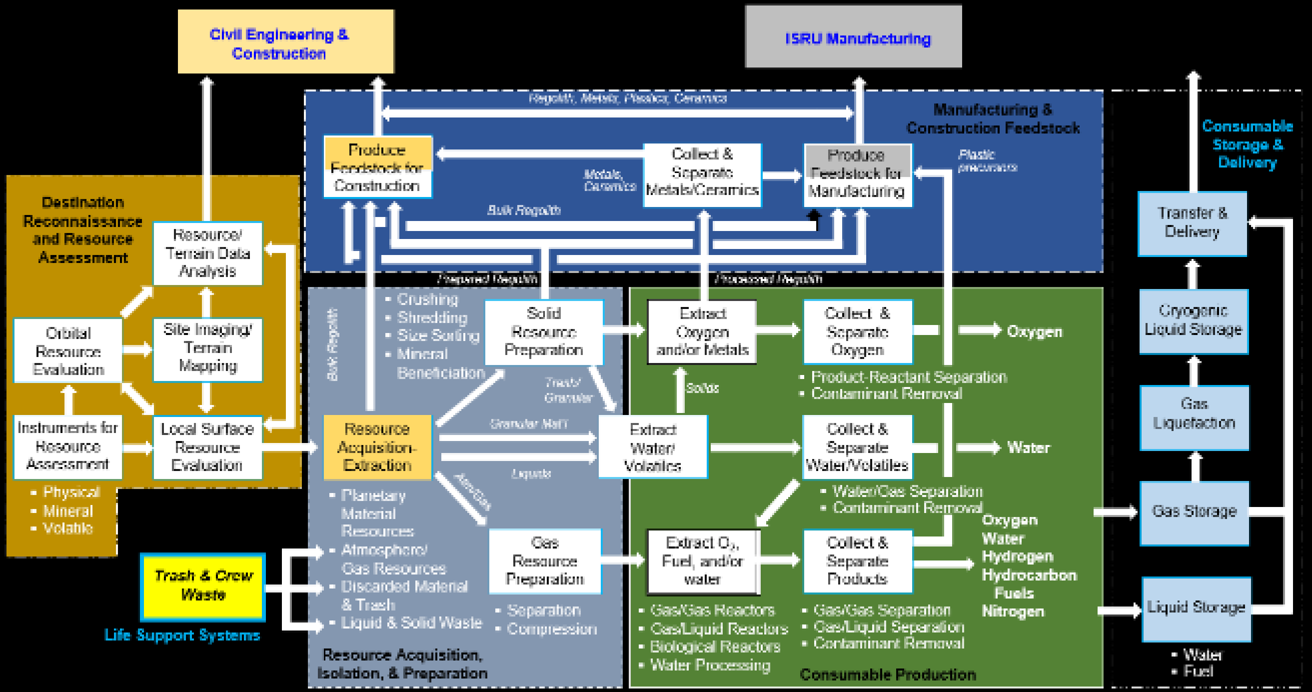
Resource Processing for Production of Manufacturing and Construction Feedstock

- In Situ Excavation and Movement for Construction
- Resource Preparation for Construction Feedstock
- Material transfer
- Resource Processing to Extract Metals/Silicon
- Resource-Trash/Waste Gas Processing to Produce Methane/Plastics

Cross Cutting

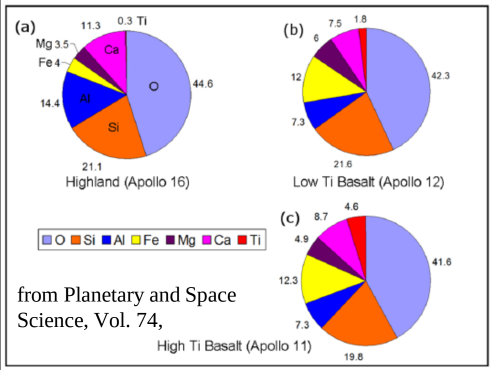
- Planetary Simulants for Test & Verification
- Planetary Regolith/Environment Test Chambers

- **Functional Breakdown and Flow Diagram used to understand:**
  - Technology State of the Art and gaps
  - Connectivity Internally and with other disciplines
  - Influence of technologies on complete system and other functions
- **ISRU functions have shared interest w/ Autonomous Excavation, Construction, & Outfitting (AECO)**
  - Destination Reconnaissance
  - Resource Excavation & Delivery
  - Construction Feedstock Production



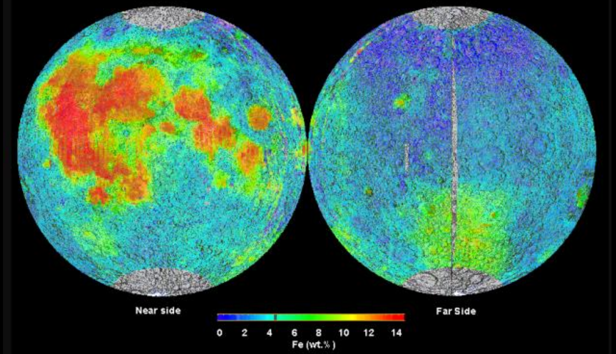
Lunar Resources for Commercial and Strategic Interests

Elements in Lunar Regolith

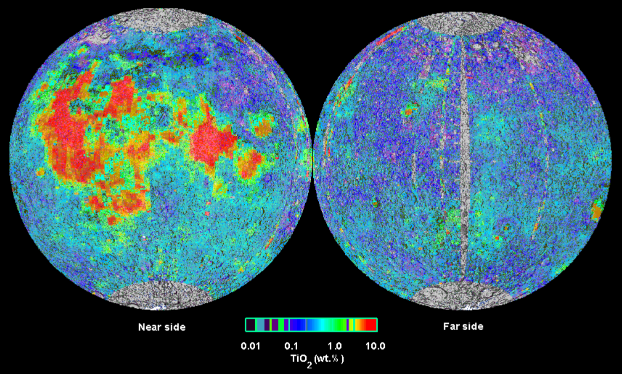


from Planetary and Space Science, Vol. 74,

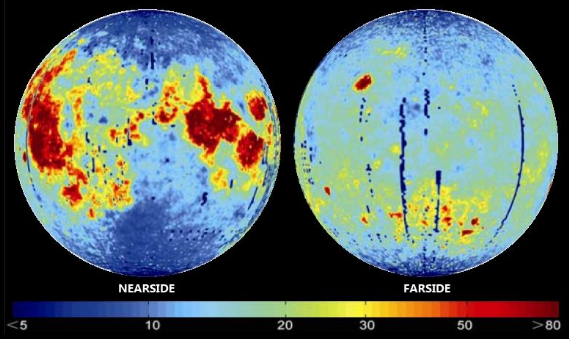
Clementine Iron Map of the Moon
Equal Area Projection



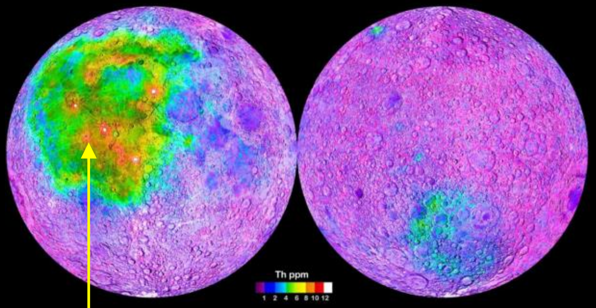
Clementine Titanium Map of the Moon
Equal Area Projection



Estimated concentration of 3He
(parts per billion by mass)



from *Icarus*, Vol. 190, Fa W and Jin Y-Q, 'Quantitative estimation of helium-3 spatial distribution in the lunar regolith layer', 15-23,



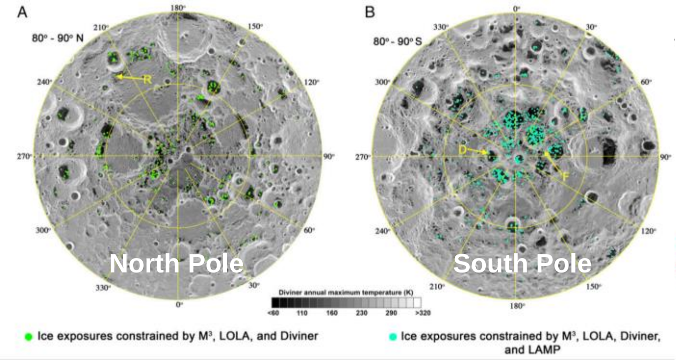
Indication of where KREEP is
(Procellerum KREEP Terrane)
Prettyman et al., 2006;

Rare Earth Elements

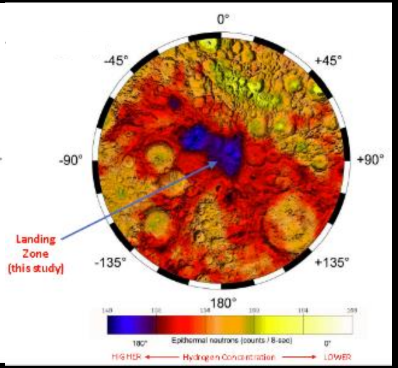
		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Pr	ppm	13	---	7	9.2
Nd	ppm	63	40	39	41.5
Sm	ppm	21	14	13	7.05
Eu	ppm	2.2	1.9	1.7	2
Gd	ppm	27	20	15	6.2

Evidence of Water & Volatiles at the Lunar Poles

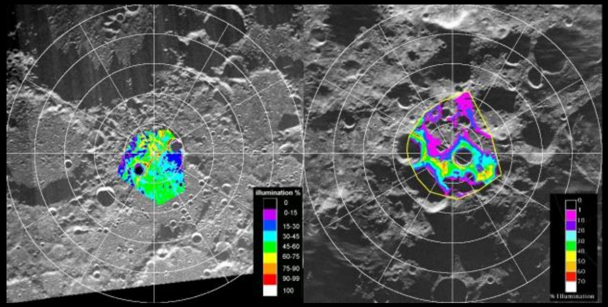
Spectral Evidence (Li, et. al)



Neutron Evidence of Hydrogen



Polar Lighting Maps *(from P. Spudis)*



Vapor Mobilized Elements

		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Ag	ppb	1.5	18	9	75
Cd	ppb	10	100	50	150
In	ppb	3	5	<10	25
Te	ppb	16	72	---	1
Se	ppm	0.7	1.6	0.8	0.05

From Bob Wegeng/PNNL

LCROSS Impact Volatiles

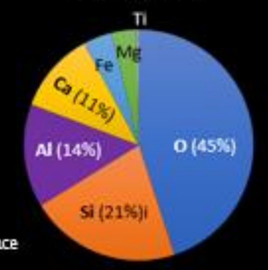
	Concentration (% wt)*
H_2O	5.5
CO	0.70
H_2	1.40
H_2S	1.74
Ca	0.20
Hg	0.24
NH_3	0.31
Mg	0.40
SO_2	0.64
C_2H_4	0.27
CO_2	0.32
CH_3OH	0.15
CH_4	0.03
OH	0.00
H_2O (adsorb)	0.001-0.002
Na	

Table courtesy of Tony Colaprete

Time and Spatial Evolution of Lunar Resources and Commodities for Commercial and Strategic Interests

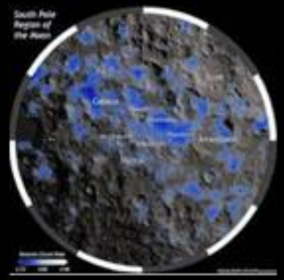
- ISRU starts with the easiest resources to mine, requiring the minimum infrastructure, and providing immediate local usage
- The initial focus is on the lunar South Pole region (highland regolith and water/volatiles in shadowed regions)
  - ISRU will evolve to other locations, more specific minerals, more refined products, and delivery to other destinations

1. Polar Highland Regolith
(Oxygen, Aluminum, Silicon)



from Planetary and Space Science, Vol. 74,

2. Polar Water/Volatiles



LCROSS Impact Volatiles	Concentration (% wt)
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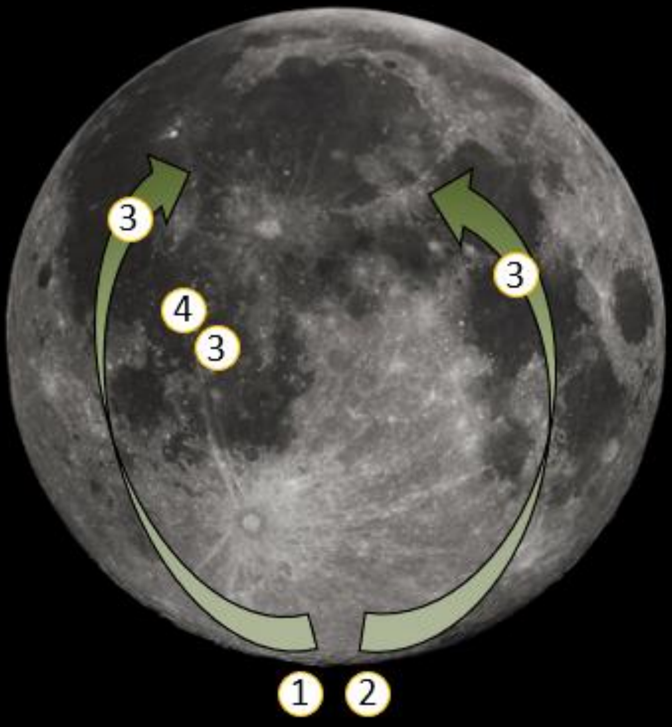
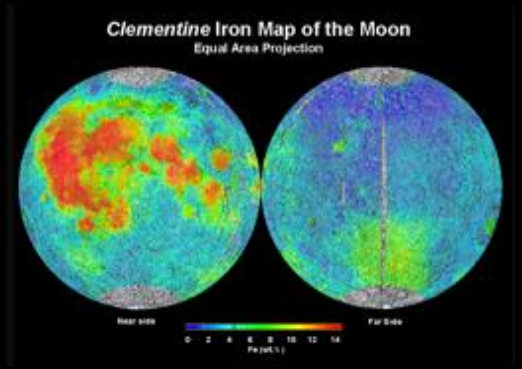
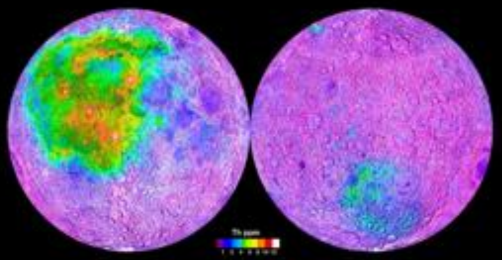


3. Ilmenite and Pyroclastic Glass
(Iron, Titanium, Solar Wind Volatiles)



4. Rare Earth Elements & Thorium



Indication of where KREEP is
(Procellerum KREEP Terrane)

Lunar ISRU Commodities

- **Water (and Volatiles) from Polar Regolith**
  - Form, concentration, and distribution of Water in shadowed regions/craters is not known
    - Technologies & missions in work to locate and characterize resources to reduce risk for mission incorporation
  - Provides 100% of chemical propulsion propellant mass (O_2/H_2)
  - ➢ Polar water is "Game Changing" and enables long-term sustainability
    - Strongly influences design and reuse of cargo and human landers and transportation elements
    - Strongly influences location for sustained surface operations

- **Oxygen/Metal from Regolith**
  - Lunar regolith is >40% oxygen (O_2) by mass
    - Polar highland regolith: mostly anorthosite rich in aluminum and silicon; poor in iron
    - Equatorial mare regolith: regions of high iron/titanium, KREEP, and pyroclastic glasses
  - Technologies and operations are moderate risk from past work and can be performed anywhere on the Moon
  - Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth); O_2 for EVA, rovers, Habs.
  - ➢ Experience from regolith excavation, beneficiation, and transfer applicable to mining Mars hydrated soil/minerals for water and *in situ* manufacturing and constructions

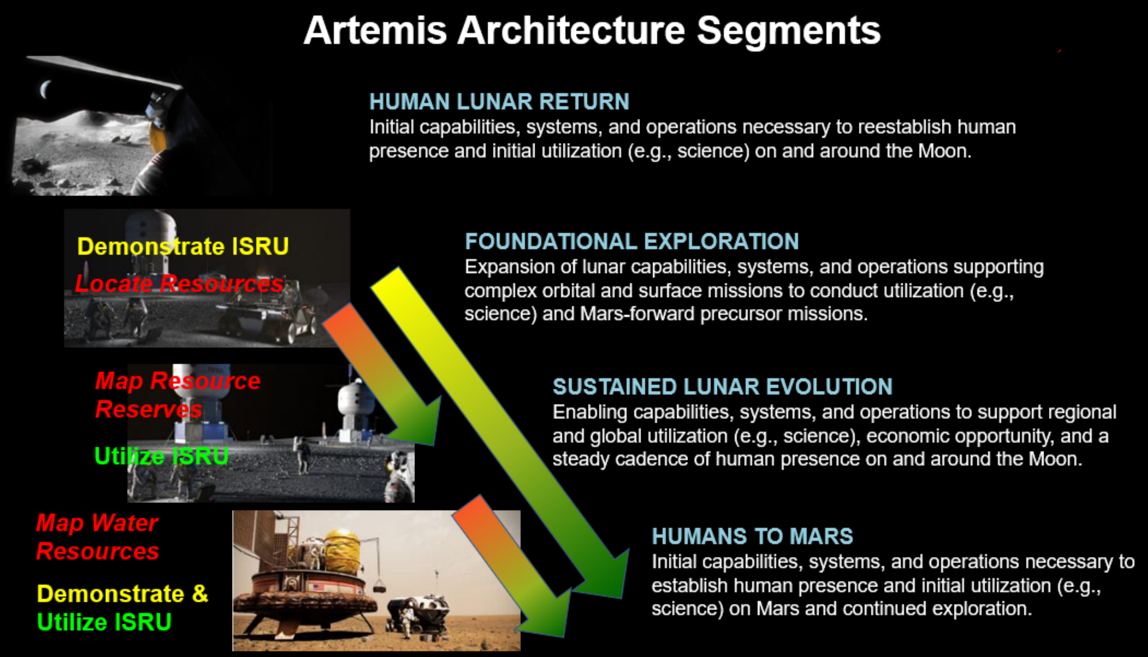
- **Propellants/Fuels and Life Support Consumables**

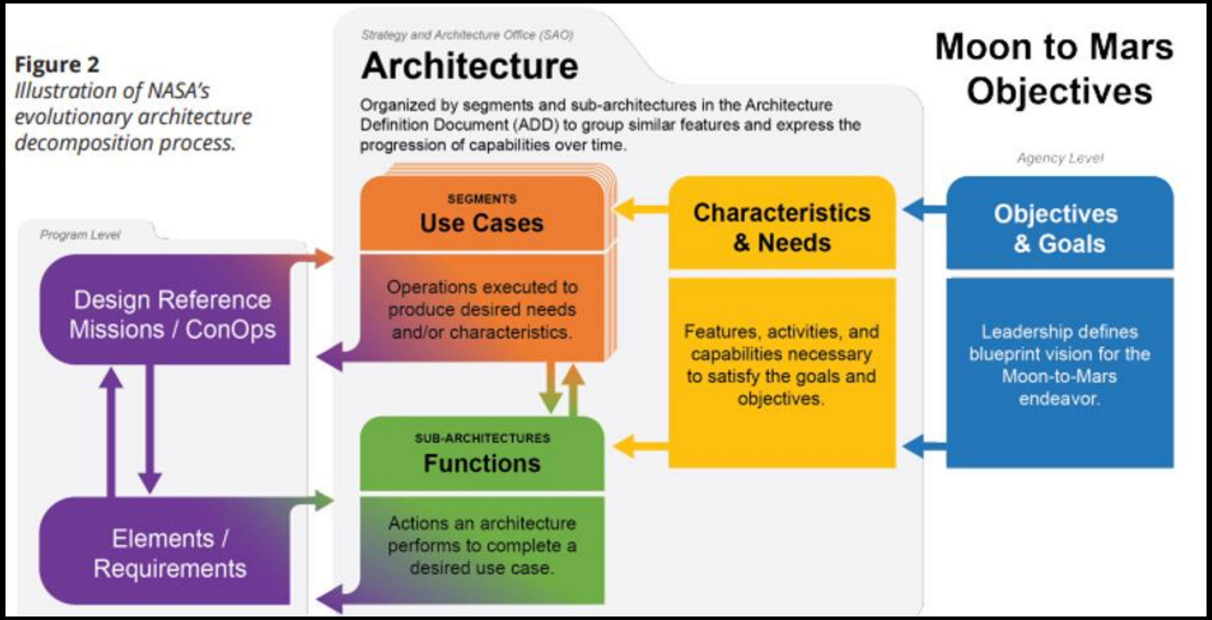
- **Manufacturing & Construction Feedstock**
  - Bulk or refined regolith (size sorted/mineral beneficiation) forms the bulk of the construction feedstock
  - Metals and slag from oxygen extraction can be used or modified as feedstock
  - Chemical and biological processing to produce binders and further refine construction materials
  - ➢ Requires close ties to In Space Manufacturing (ISM) and Autonomous, Excavation, Construction and Outfitting (AECO)

- **Support for Plant/Food/Nutrient Production**
  - Bulk or refined regolith (size sorted, mineral beneficiation, milled, treated) for plant growth media
  - Chemical and biological processing (esp. of carbon/water) of wastes and in situ resources to produce nutrient and food precursors
  - ➢ Requires close ties to Life Support Systems

How Does ISRU Fit Into Plans for Artemis?

Overview of ISRU Involvement in Artemis





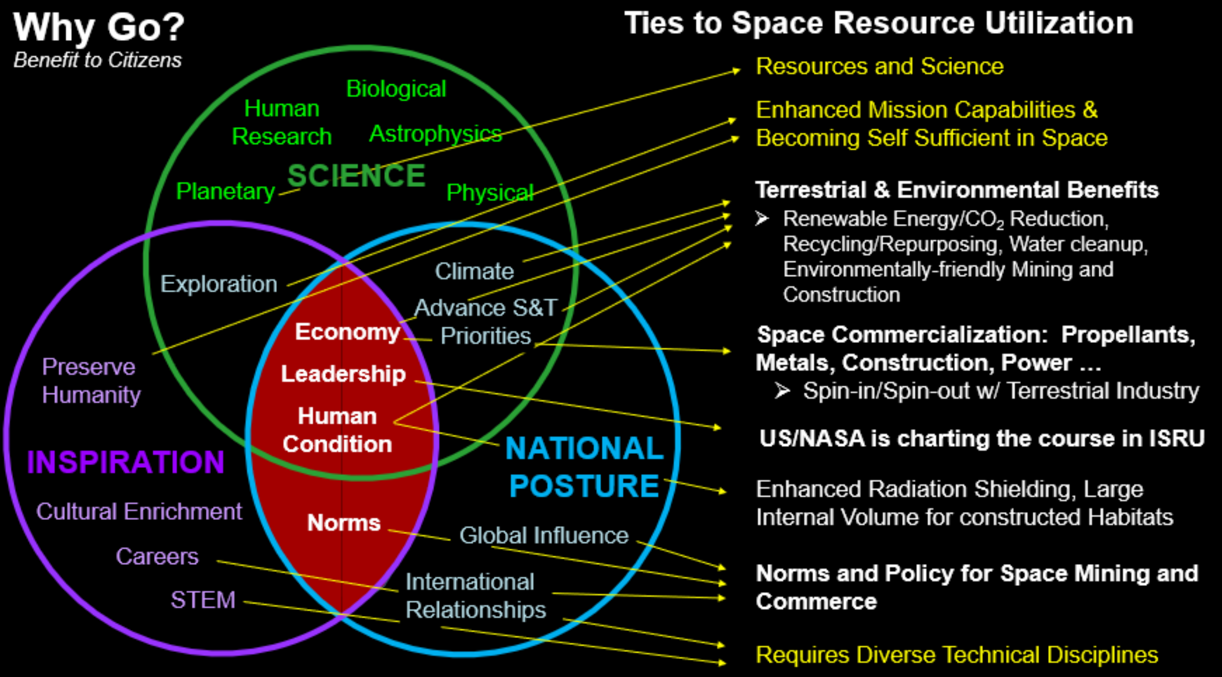
Resource Assessment and Mapping and ISRU Involvement will Evolve with Each Artemis Architecture Segment

Artemis Architecture Definition Document (ADD)

- Establishes the process, framework, and decomposition of objectives to empower the executing systems', programs', and projects' success in achieving human exploration of the cosmos."
- ISRU Added as a 'Sub-Architecture' in Rev 1. in 2023
- Currently defining Characteristics & Needs, Use Cases, and Functions for HLR and FE segments

Overview of Why ISRU In Human Exploration

*NASA Moon to Mars (M2M) Blueprint Objectives officially released in Sept. 2022 at IAC; Updated 4/2023



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[LM]	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

⇧ = Key ISRU M2M Objectives

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

3 Pillars of Human Exploration of Space & Ties to ISRU Development and Use

Moon to Mars Objectives Tied to 4 Major Items

- Resource Assessment
- ISRU and Usage
- Responsible Use of Space & Space Mining
- Recurring Tenants

Regulatory: Aiming Toward Establishing Stable Legal and Regulatory Frameworks

Overarching Legal Framework for Space Resources

- **Art. I:** "Outer space, including the Moon and other celestial bodies, shall be free for exploration and use by all States "
- **Art. II:** "Outer space, including the moon and other celestial bodies, is not subject to national appropriation
- **Art. IX:** State parties "shall conduct all their activities in outer space . . . with due regard to the corresponding interests of all other States Parties to the Treaty."

Non-Binding Agreement on Conduct for Space Resources

Space Resources

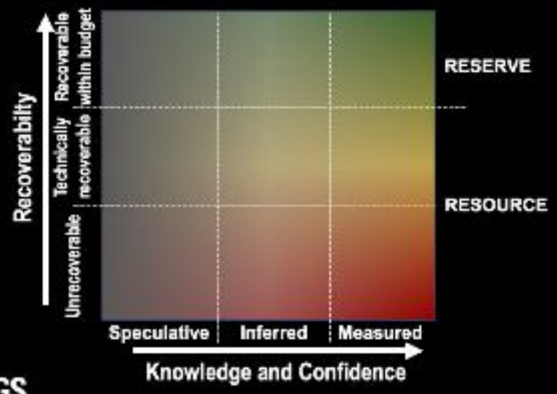
The ability to extract and utilize resources on the Moon, Mars, and asteroids will be critical to support safe and sustainable space exploration and development.

The Artemis Accords reinforce that space resource extraction and utilization can and will be conducted under the auspices of the Outer Space Treaty, with specific emphasis on Articles II, VI, and XI.

UN Activities on Space Resources

UN Working Group on Legal Aspects of Space Resource Activities

Methodology for Quantitative Lunar Resource Assessment



USGS

National Laws for Space Resources

114th Congress, 1st Session — HOUSE OF REPRESENTATIVES — Report 114–153

SPACE RESOURCE EXPLORATION AND UTILIZATION ACT OF 2015

US

Luxembourg: Law on Use of Resources in Space Adopted

Luxembourg

Japan passes space resources law

Japan

UAE SPACE LAW DETAILS ANNOUNCED TO FACILITATE SPACE SECTOR DEVELOPMENT

UAE

How Will ISRU Be Developed and Demonstrated?

Space Mining/ISRU Must Operate as Part of A Larger Architecture

- Elements and interdependencies must be designed with Space Mining product usage in mind from the start to maximize benefits
  - Transition from Earth-supplied to ISRU-supplied
  - Guided by overarching Site Master Plan and Concept of Operations

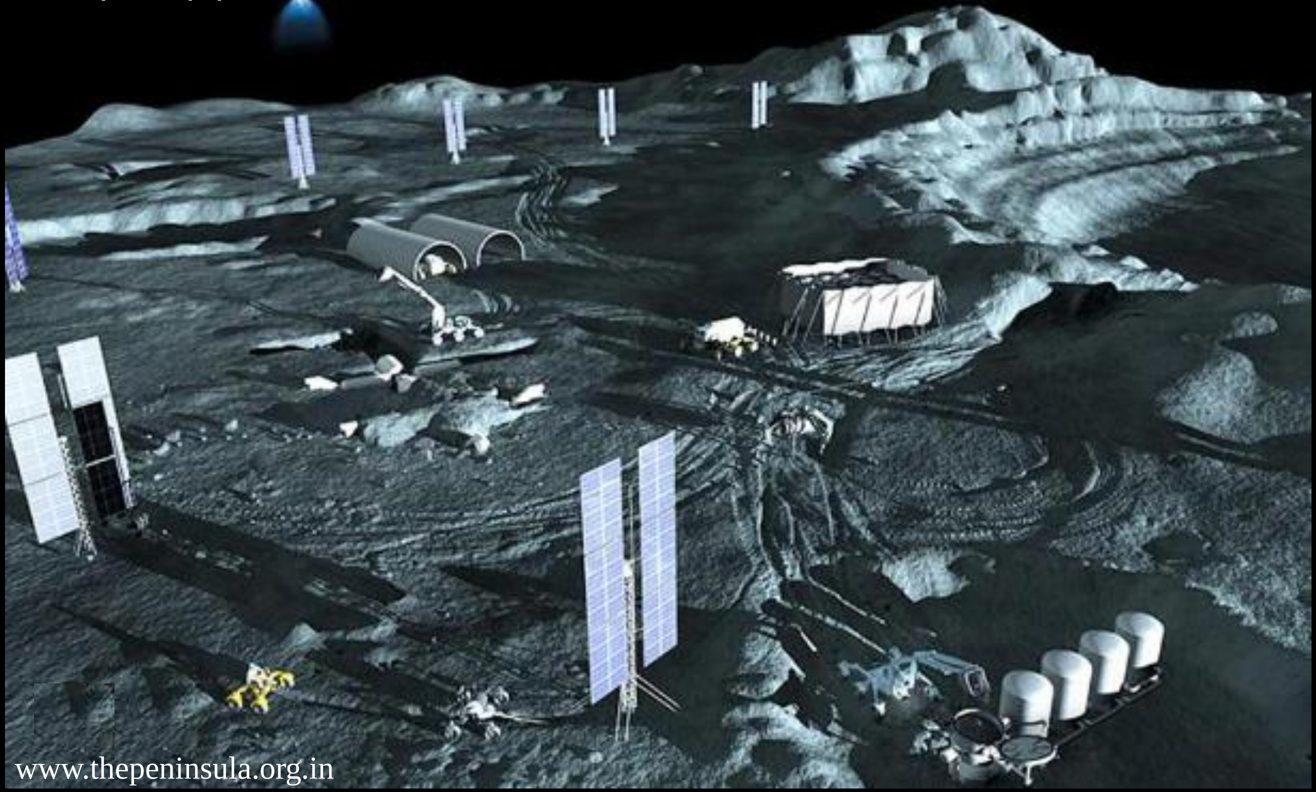
Transportation to/from Site:
- Delivery (P)
- Propellants & Depots (S)

Power:
- Generation, Storage, & Distribution (P)
- ISRU-derived electrical /thermal (S)

Communications & Navigation (P)
- To/From Site
- Local

Space Mining

Coordinated Mining Ops:
Areas for:
i) Excavation
ii) Processing
iii) Tailings
iv) Product Storage



Maintenance & Repair Logistics Management
- Replacement parts (P)
- Feedstock (S)

Living Quarters & Crew Support Services
- Water, O_2, H_2, Gases (S)
- Trash/waste (P)
- Nutrients(S)

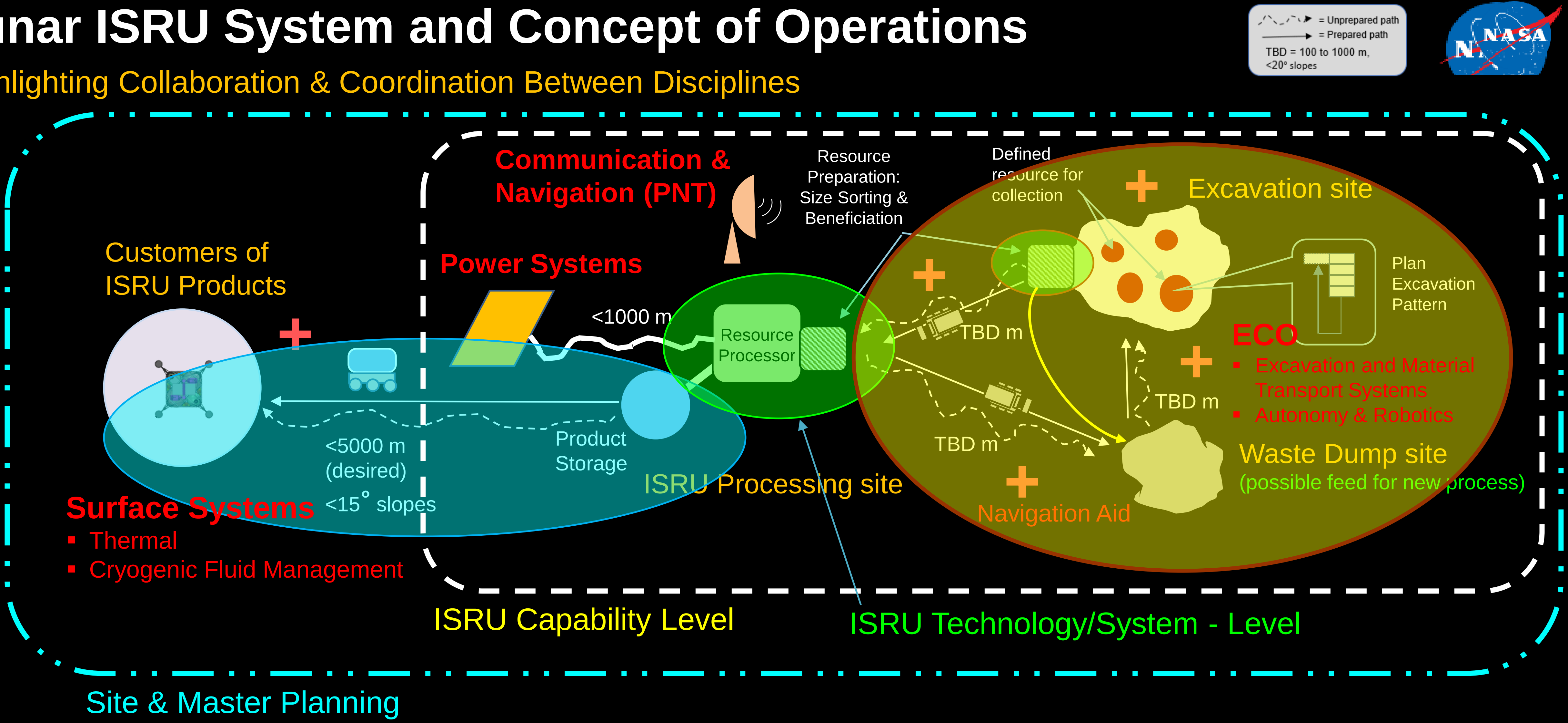
P = Provided to ISRU
S = Supplied by ISRU
Italic = Other Disciplines

Commodity Storage and Distribution:
- Water & Cryogenic Fluids (CFM)
- Manufacturing & Construction Feedstock

Construction and Outfitting
- Feedstock for roads and structures (S)

Lunar ISRU System and Concept of Operations

Highlighting Collaboration & Coordination Between Disciplines

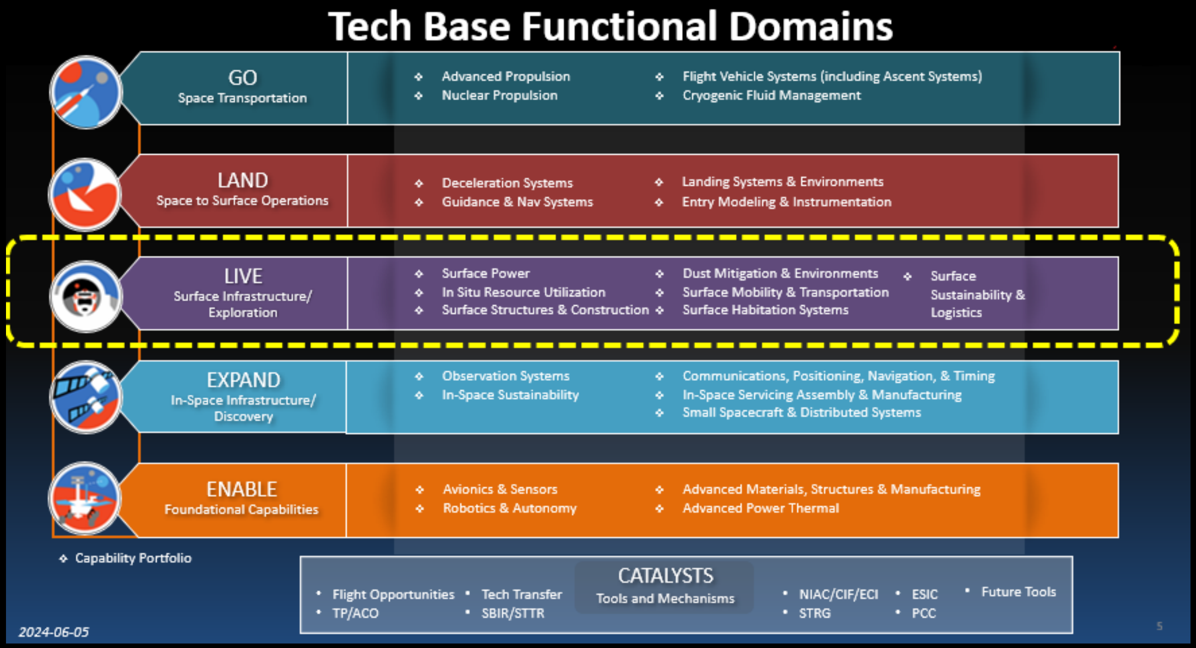


Two levels of Development, Integration, and Testing

- ISRU Technology/System level development and testing (internal to ISRU domain)
- ISRU Capability level development and testing (coordinate across domains)

ECO = Excavation, Construction & Outfitting
PNT = Position, Navigation & Timing

NASA Space Technology Mission Directorate (STMD) and ISRU Reorganizing and Prioritizing



Overall Priority	Shortfall ID (blue text if top 3 in category)	Category
53	1578: Extraction and separation of water from extraterrestrial surface material	ISRU
64	1577: Perform resource reconnaissance to location and characterize resources and estimate reserves	ISRU
68	1580: Extraction and separation of oxygen from extraterrestrial minerals	ISRU
79	1583: Produce propellants and mission consumables from extracted in-situ resources	ISRU
103	1585: Extraterrestrial surface environmental simulators, test facilities, and test sites	ISRU
107	1581: Extraction and separation of extraterrestrial atmospheric resources and gaseous products/reactants	ISRU
110	1582: Extraction and separation of metals/metalloids from extraterrestrial minerals	ISRU
117	581: ISRU System Modeling	ISRU
142	1584: Produce manufacturing and construction feedstock from extracted in-situ resources	ISRU
169	1579: Extraction and separation of non-water volatile resources from lunar regolith	ISRU
178	1593: Lunar Surface Power Generation from ISRU Derived Resources	Power
183	1594: Martian Surface Power Generation from ISRU Derived Resources	Power
92	1485: On-Surface Manufacturing of Parts/Products from Surface & Terrestrial Feedstocks	Advanced Manufacturing
145	425: On-surface ISRU-based Construction of Vertical Structures	ECO
160	666: On-surface ISRU-based Construction of Horizontal Structures	ECO
58	1221: Mars Ascent Propulsion	Propulsion: Non-nuclear

NASA Space Technology Mission Directorate (STMD) Reorganizing around Domains & Capabilities

- Organization previously organized around TRL programs

NASA STMD Activity Priorities Based on Stakeholder Ranking

- 187 Shortfalls (covering over several hundred gaps) were created, ranked, and prioritized based on Customer & Stakeholder inputs

Overview of ISRU Development Approach and Plans

Market Transparency
- **Define Initial and Long-term Customer Needs for ISRU-derived Products**
  - Work within NASA and International Partners
  - Work with Industry: Utilize Lunar Surface Innovation Consortium

Technology Innovation
- **Advance ISRU technologies and systems for lunar missions by utilizing NASA solicitations, public private partnerships, internal/external investments**
  - Perform and support extensive development and integration/testing

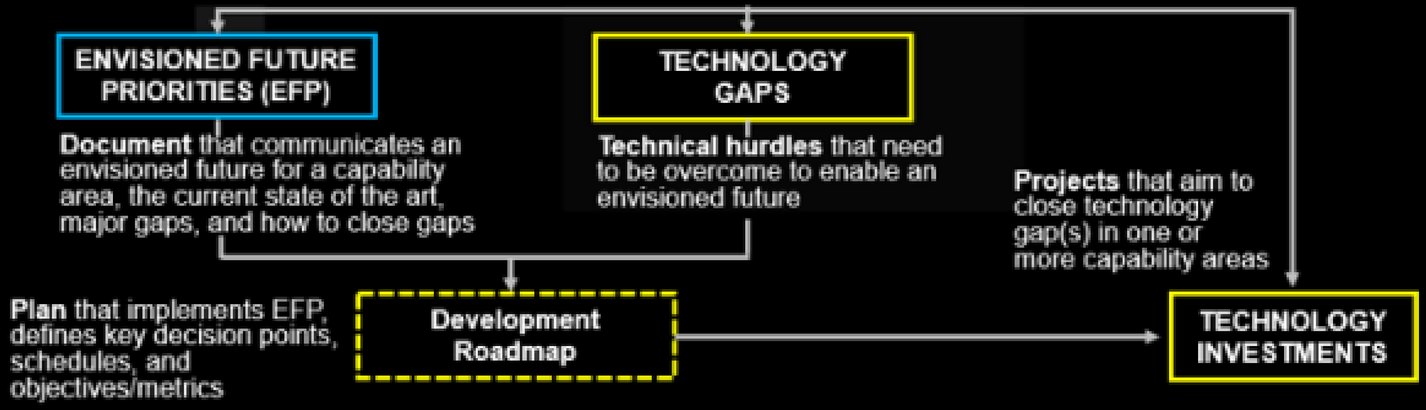
Scale-up Investment
- **Reduce Risk and Promote Investment in ISRU Systems and Products**
  - Coordinate requirements, development, and implementation of infrastructure required for ISRU operations
  - Provide to industry key and enabling NASA capabilities and resources. Support data buys for lunar resource understanding and ISRU technologies/operations
  - Perform and support lunar resource assessment and technology demonstrations (CLPS, HLS, Int'l Partner, Industry)

Readiness for Disruption
- **Promote Industry-led ISRU Development thru End-to-End ISRU Production of Commodities (i.e. Pilot Plant) and usage**
  - Production at sufficient scale to eliminate risk of Full-scale system
  - Promote use of ISRU-derived commodity initially in non-mission critical applications to build market and trust

Circular Economy
- **Promote tracking and usage of all product/waste streams**
  - Minimize waste, promote recycling, refurbishment, and reuse

Plan to Achieve ISRU Envisioned Future

- Enable Industry to Implement ISRU for Artemis, Sustained Human Presence, and Space Commercialization
- ISRU must be demonstrated on the Moon before mission-critical applications are flown



Process Established to Continually Update Plan

- Envisioned Future only modified as needed
- Technology Gaps and Investments Tracked Continuously and updated once or twice a year
- Development updated to reflect changes in gap closures and investment success

What are the Challenges? - ISRU Development & Implementation

Space Resource Challenges

R1 What resources exist at the site of exploration that can be used?

R2 What are the uncertainties associated with these resources?
Form, amount, distribution, contaminants, terrain

R3 How to address planetary protection requirements?
Forward contamination/sterilization, operating in a special region, creating a special region

ISRU Technical Challenges

T1 Is it technically and economically feasible to collect, extract, and process the resource?
Energy, Life, Performance

T2 How to achieve high reliability and minimal maintenance requirements?
Thermal cycles, mechanisms/pumps, sensors/ calibration, wear

ISRU Operation Challenges

O1 How to operate in extreme environments?
Temperature, pressure/vacuum, dust, radiation, grounding/plasma charging

O2 How to operate in low gravity or micro-gravity environments?
Drill/excavation force vs mass, soil/liquid motion, thermal convection/radiation

O3 How to achieve long duration, autonomous operation and failure recovery?
No crew, non-continuous monitoring, time delay

O4 How to survive and operate after long duration dormancy or repeated start/stop cycles with lunar sun/shadow cycles?
'Stall' water, lubricants, thermal cycles

O5 How to operate responsibly with minimal impact to science and the environment

ISRU Integration Challenges

I1 How are other systems designed to incorporate ISRU products?

I2 How to optimize at the architectural level rather than the system level?

I3 How to manage the physical interfaces and interactions between ISRU and other systems (esp. with International Partners and multiple companies)?

I4. How to ensure critical exploration and infrastructure capabilities are delivered in the correct sequence and in a timely manner?

I5. How to grow a commercial ecosystem of supply-demand?

ISRU Challenges			Earth	Orbital	Surface
Resources	R1	What resources exist at the site that can be used?	S	S	P
	R2	What are the uncertainties associated with these resources?	S	S	P
	R3	How to address planetary protection requirements?	P		V
Technical	T1	Is it technically feasible to collect, extract, & process resources?	P		V
	T2	How to achieve high reliability/minimal maintenace?	P		V
Operational	O1	How to operate in extreme environments?	S/V	P_{NEA}	P
	O2	How to operate in low/micro gravity?	S	P_{NEA}	P
	O3	How to achieve long duration, autonomous operation?	P		V
	O4	How to survive and operation after long duration dormancy	P		V
	O5	How to operate responsibly w/ minimum impact to science/env.	P		V
Integration	I1	How other systems designed to incorporate ISRU products?	P		V
	I2	How to optimize at the architectural level with ISRU?	P		V
	I3	How to manage the interfaces/interactions with other systems?	P		V
	I4	How to deliver in the correct sequence and timely manner?	S		P
	I5	How to grow a commercial ecosystem of supply-demand?	S		V/P

P = Primary Location, S = Support Location, V = Validation

Needs to be performed in lunar environment with actual lunar regolith

Needs significant integrated system testing under analog and lunar environment simulation capabilities

'Responsible Mining' is now becoming very important

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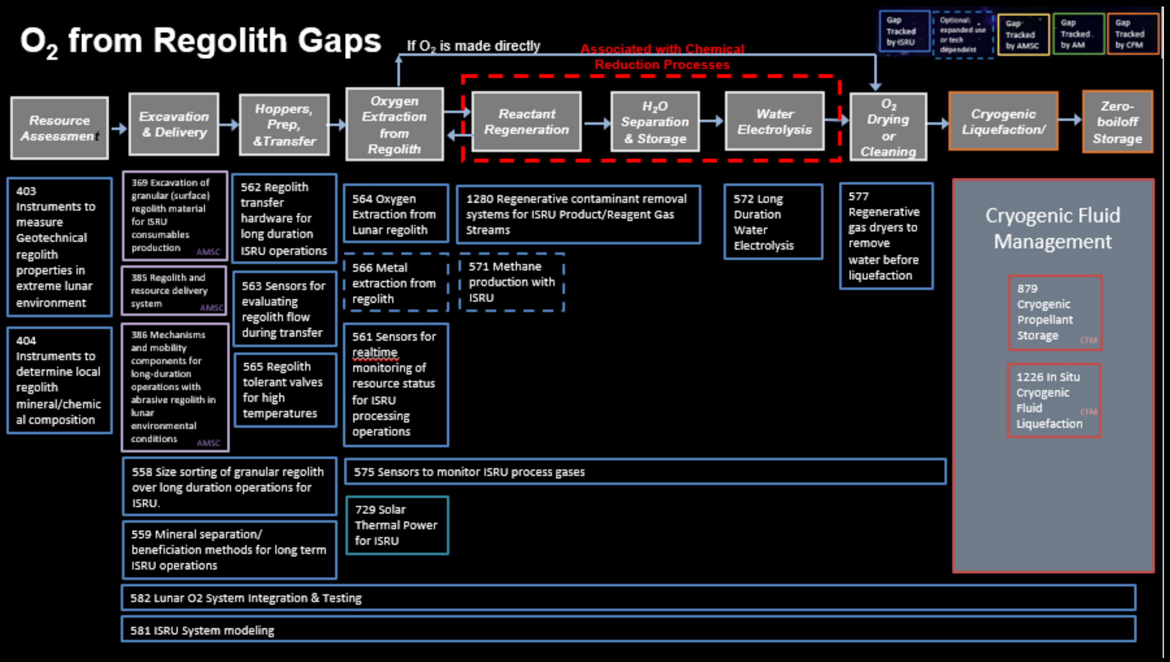
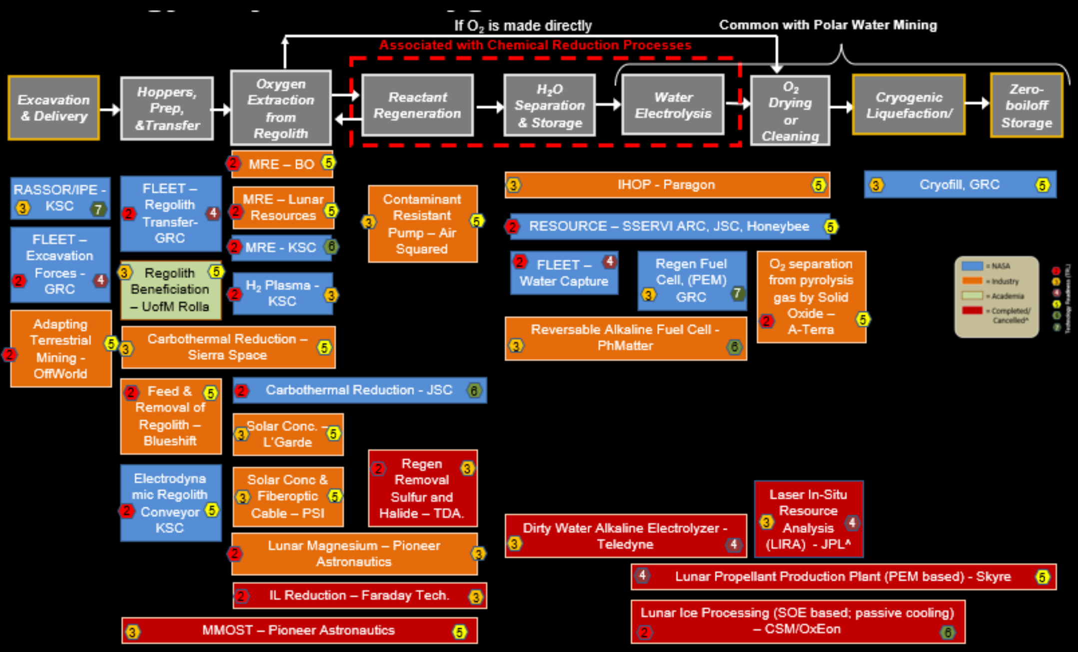
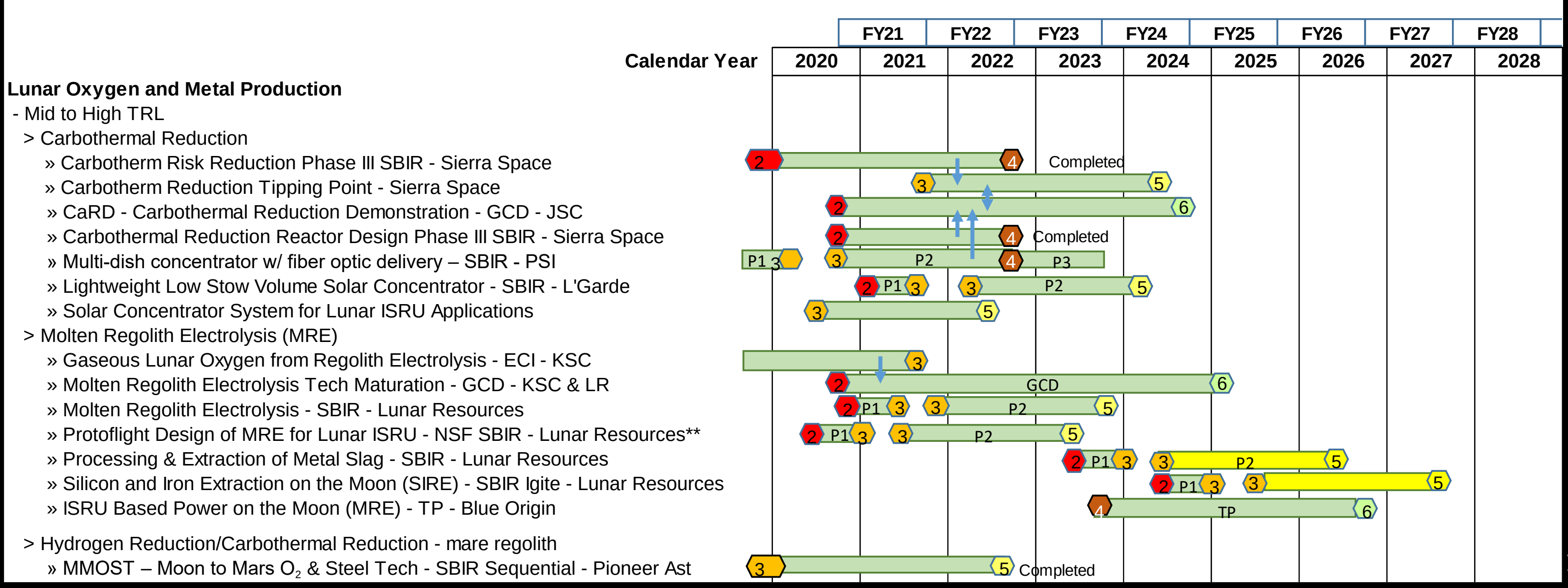
- Most challenges and risks to ISRU development and incorporation can be eliminated through design and testing under Earth analog or environmental chamber testing at the component, subsystem, and system level
  - ➢ **Adequate simulants are critical for valid Earth based testing**
- Critical challenges/risks associated with fully understanding the extraterrestrial resource (form, concentrations, contaminants, etc.) and ISRU system operation under actual environmental conditions for extended periods of time can only be performed on the extraterrestrial surface
- Product quality based on actual in situ resource used should be validated at the destination
- ISRU precursors/demonstrations are extremely beneficial for validation of Earth-based testing and analysis

Define, Advertise, and Track Technology Gaps and Efforts





- ISRU System Defined in Functional Block Diagrams and Technology Gaps Assigned to Functions
- On-going Activities tracked by ISRU System functions and areas with starting and ending TRLs
- Over 50 projects in 2023 aimed at ISRU gaps



Lunar Polar Ice Resource Assessment – Prototype to Flight Hardware

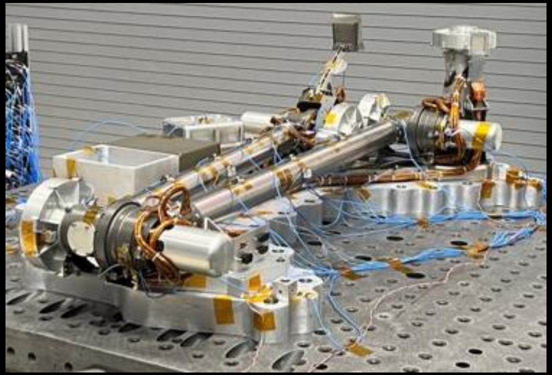
*Not all funded efforts are designated as ISRU

- **Acquire Regolith Samples**
  - ColdARM – JPL – GCD* – Flight cancelled
  - LUnA: Lunar Under-actuated robotic Arm Maxar - TP
  - Trident Auger – Honeybee Robotics – PRIME-1 & VIPER
  - Honeybee PVEx Drill – SSEVI RESOURCE project*
  - IPEx: ISRU Pilot Excavator – KSC – GCD*
  - MEERCAT: Multifunction End Effector for Regolith Construction, Acquisition, & Transfer - KSC
- **Instruments for Physical/Geotechnical Characterization**
  - Soil Properties Assessment Resistance & Thermal Analysis (SPARTA) – JPL – SMD*
  - SPARTA Blue Origin Flight – JPL - FO
- **Instruments for Mineral/Elemental Characterization**
  - *SMD & CLPS Selections**
- **Instruments for Ice/Volatile Characterization**
  - Polar Resources Ice Mining Experiment-1 – NASA KSC & Honeybee Robotics – GCD
  - Light Water Analysis & Volatile Extraction (Light WAVE) – NASA JSC – GCD - Cancelled

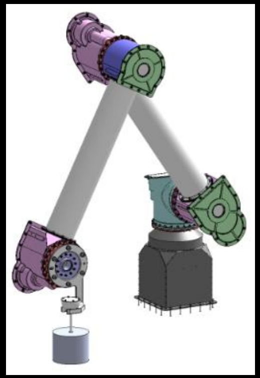
IPEx - KSC

Selected for CLPS (by SMD and STMD)

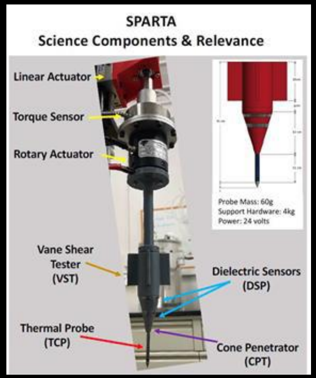
Astrobotic 2022	IM Prime-1 2022 (SP)	Firefly 2023	Masten 2023 (SP)	Ast. VIPER 2023 (SP)	
					Mineral Characterization
X			X	X	NIRVSS - InfraRed Spec
			X		L-CIRiS - Compact InfraRed Imaging System
					eXTraterrestrial Regolith Analyzer for Lunar Soil - XRD/XRF
					Ultra-Compact Imaging Spectrometer - Shortwave IR
					BECA - Gamma Ray Spectrometer w/ Pulsed Neutrons
					Volatile - Direct Measurement
	X		X	X	MSolo - Mass Spectrometer
X					PITMS - Ion-trap Mass Spectrometer
					CRATER - Laser-based Mass Spectrometer
X			X	X	NIRVSS -InfraRed Spec (surface and bound H_2O/OH)
					Hydrogen Measurement
X			X		NSS - Neutron Spectrometer
					NMLS - Neutron Measurement at the Lunar Surface
					Imager
			X		Heimdall - Digital Video Recorder/4 Cameras
					Physical Properties/Acquisition
		X			LISTER - Heatflow Probe
		X			RAC - Regolith Adherence Characterization
		X			Electrodynamic Dust Shield (EDS)
		X			PlanetVac - Pneumatic Transfer
			X		SAMPLR - Arm Scoop
					ColdARM - Arm Scoop
	X			X	Trident - Auger Drill
					PVEx - Coring Drill
					MicroRovers/Hoppers
					CubeRover (SBIR)
			X		MoonRanger with NS (LSIPT)
					L-PUFFER/CADRE (JPL)
					NeuRover (SBIR)
	X				Mobile Autonomous Prospecting Platform (Commercial)
	X				Micro-Nova



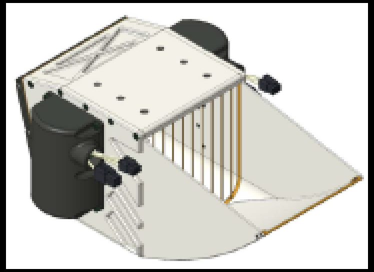
COLDArm - JPL



LUnA - Maxar



SPARTA - JPL



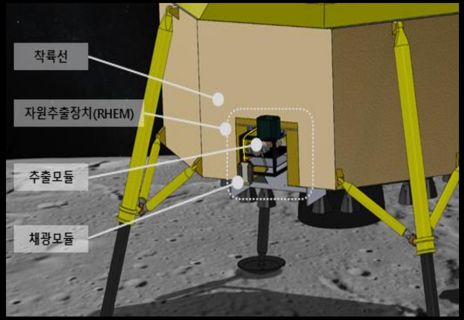
MEERCAT- KSC

International ISRU – Water/Volatile Assessment & Processing

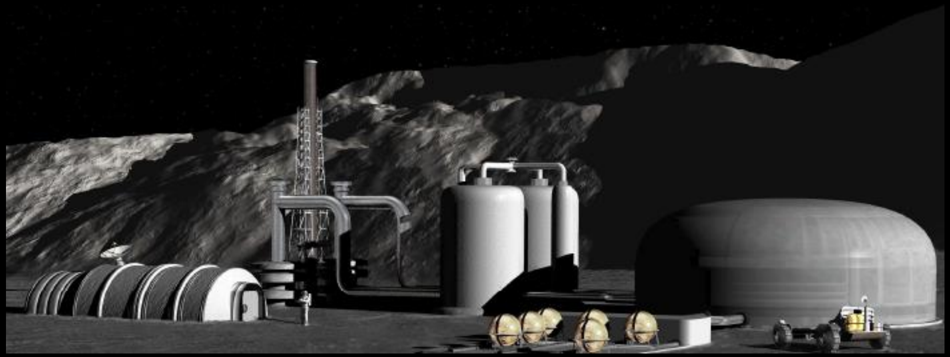
- **Water/Volatile Resource Assessment Mining**
  - ESA Package for Resource Observation and in-Situ Prospecting for Exploration, Commercial exploitation and Transportation (PROSPECT) instrument – CLPS 2026 mission
  - JAXA Lunar Polar Exploration (LUPEX) rover mission
  - JAXA water mining pilot to full scale system concept
  - Korea/KIGAM Lunar Regolith Extraction Demonstrator (LUVED) mineral and solar wind volatile resource assessment

LUPEX - JAXA

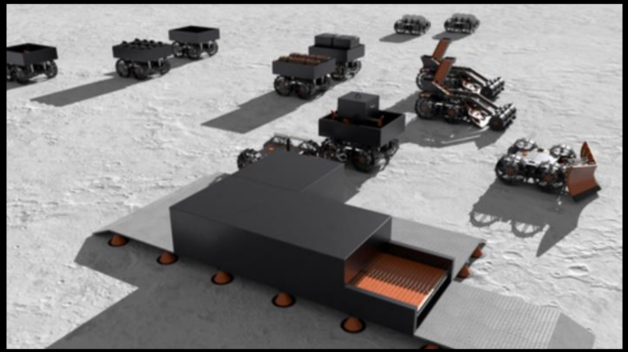
PROSPECT - ESA



LUVED - KIGAM



Polar Water Mining - JAXA



Polar Water Mining – LSA & Offworld

Lunar Polar Ice/Water Mining – Current Development

1. Excavation/Acquisition and Processing Reactor

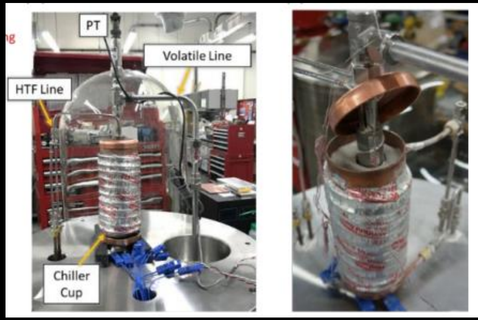
Loose Regolith Excavation – KSC

NASA's BREAK THE ICE LUNAR CHALLENGE

Lunar Auger Dryer – JSC

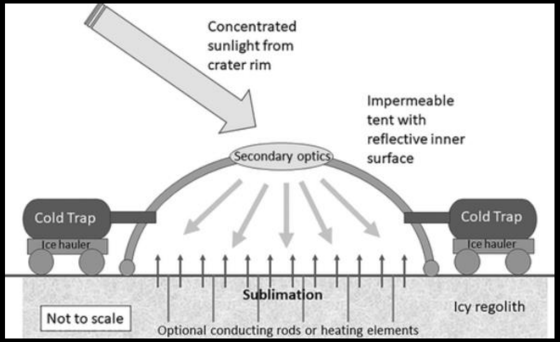
2. Subsurface Heating - Contained

Planetary Volatile Excavator (PVEx) – Honeybee Robotics

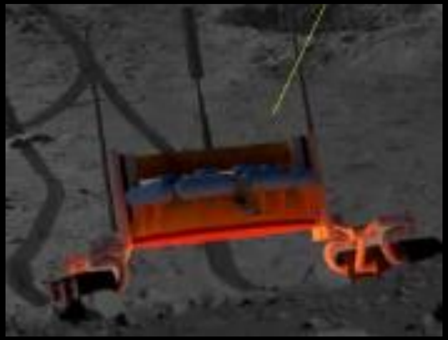


Thermal Extraction w/ PVEx – Advanced Cooling Technology

3. Subsurface Heating/Ablating and Volatile Release Capture

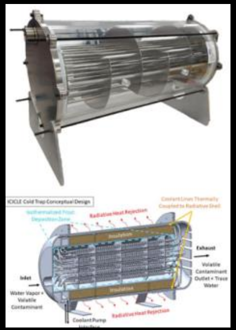


Thermal Lunar Mining – Colorado School of Mines



Microwave/RF Lunar Mining – TransAstra

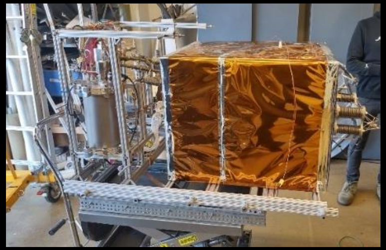
4. Water/Volatile Capture and Cleanup under development/consideration



ICICLE water collection – Paragon Space

IHOP water cleanup & electrolysis – Paragon Space

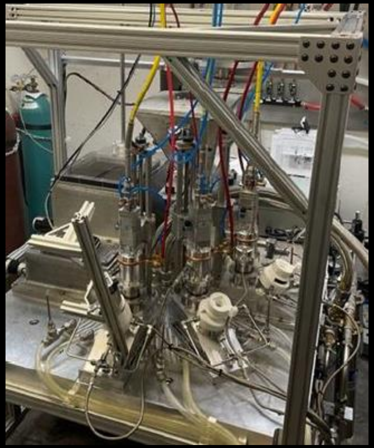
Lunar water collection& Electrolysis – CSM & OxEon



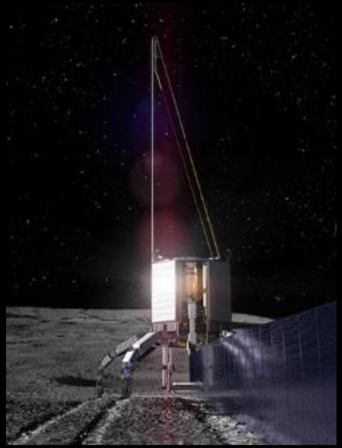
Lunar Oxygen (Metal) Extraction from Regolith - Current Development

Mid-TRL

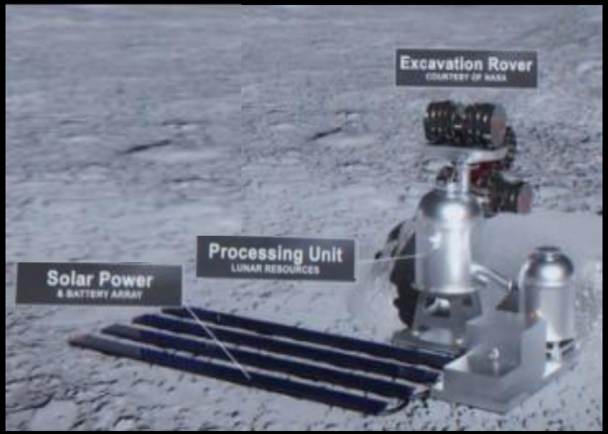
- **Carbothermal Reduction**
  - Carbothermal Reduction Reactor Design – Sierra Nevada Corp (SNC) – 2 SBIR Phase IIIs, and COPR Tipping Point
  - CaRD - Carbothermal Reduction Demonstration – JSC – GCD
- **Molten Regolith Electrolysis (MRE) for O_2/Metals**
  - ISRU Based Power on the Moon – Blue Origin – TP
  - Molten Regolith Electrolysis Tech Maturation – KSC – GCD and ECI
  - Molten Regolith Electrolysis - Lunar Resources – Several NASA SBIR Phase I/II and NSF SBIR Phase II
- **Moon to Mars Oxygen and Steel Technology (CO/H_2 Reduction)** - Pioneer Astronautics - SBIR Sequential – Completed



Carbothermal Reduction – Sierra Space



Molten Regolith Electrolysis – Blue Origin



Molten Regolith Electrolysis – Lunar Resources

Hydrogen/Carbothermal Reduction – Pioneer Astronautics

Lunar Oxygen (Metal) Extraction from Regolith - Current Development

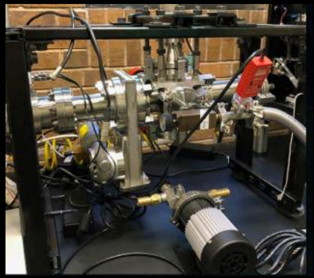
Low-TRL

- **Carbothermal Reduction**
  - Lunar Magnesium from Beneficiated Regolith – Pioneer Astronautic – SBIR Phase I
- **Molten Reduction**
  - Domed MRE – Ethos Space – *Non-NASA External Investment*
  - Novel Hollow Anode Design for Improved MRE – Northwestern Unv. – NSTGRO
  - Silicon and Iron Extraction on the Moon (SIRE) – Lunar Resources – SBIR Phase I
  - MAGMA: Molten Aluminum Generation for Manufacturing Additively – CSM - LuSTR
- **Acid Reduction**
  - Alkaline Low-Temp Aluminum from Waste Slag – Pioneer Astronautic – SBIR Phase I – Completed
- **Ionic Liquid Reduction and Electrolysis reactors for O2/Metals**
  - RRILE – Resource Recovery with Ionic Liquid for Exploration - MSFC – GCD - Completed
  - Ionic Liquid-Assisted Electrochemical Extraction of Oxygen - Faraday Technology - SBIR Phase I – Completed
  - IL-Assisted Electrochemical Extraction of Metals and Oxygen from Lunar Regolith - Faraday Technology - SBIR Phase I – Completed
  - In situ Recovery of High Purity Single Element Metals and Oxygen from Regolith using Task Specific Ionic Liquid Facilitated Electrochemical Solvent Extraction – University of Colorado-Boulder - NSTRF – Completed
  - IL Reduction of Lunar Regolith – Diatomic Space – *Non-NASA External Investment*
- **Plasma Hydrogen Reduction**
  - Plasma Hydrogen Process – KSC – CIF – Completed
- **Vapor Pyrolysis**
  - Carbothermal/Vapor Pyrolysis with Solar Concentrator – Blueshift - SBIR Phase I – Completed
  - High Purity O_2 Separation from Pyrolysis Gas – A-Terra – SBIR Phase II
  - Multi-stage O_2 & Regolith Extractor – Blueshift – SBIR Phase I
  - Terraxis IR&D (TRL 2-3) – *Non-NASA External Investment*

International ISRU – Regolith Processing

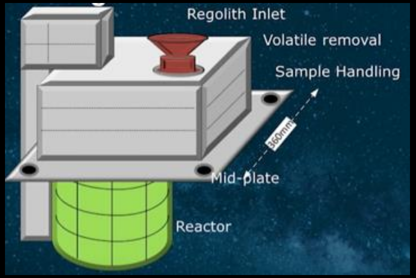
- **Hydrogen (H_2) & Hydrogen Plasma Reduction**
  - European Space Research Innovation Center (ESRIC) Europe (TRL 2) - Research with conversion of existing Hydrogen Reduction breadboard
- **Carbothermal Reduction** (Hydrogen/Methane reduction below regolith melting point)
  - Politecnico di Milano - Italian Space Agency (ASI)
  - Canadian Space Mining Corp (CSMC) - Canadian space Agency (CSA)
- **Molten Regolith Electrolysis (MRE)**
  - Helios – Israel
    - 2 flight demos in work
    - Working with terrestrial steel manufacturers on their technology which may be able to produce steel with no carbon/CO_2 emissions (https://www.fastcompany.com/90761860/a-space-tech-company-stumbled-on-a-new-way-to-cut-emissions-on-earth).
- **Molten Salt Electrolysis (MSE)**
  - European Space Research Innovation Center (ESRIC) Europe
  - Thales Alenia-UK selected 9/22 for ESA O_2 Demonstration mission. In Phase B for 2027 – Europe (TRL 3/4) (https://www.esa.int/Enabling_Support/Space_engineering_Technology/Team_chosen_to_make_first_oxygen_on_the_Moon
  - Airbus for DLR. Reactor concept for CLPS-class mission

H_2 Reduction - ESRIC

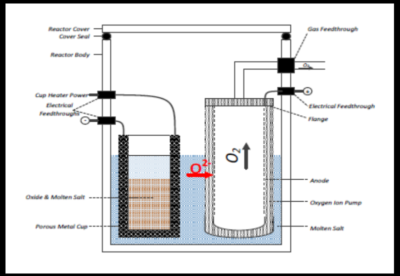


Molten Regolith Electrolysis - Helios

Molten Salt Electrolysis - ESRIC



Molten Salt Electrolysis - Thales



Molten Salt Electrolysis - Airbus

New Shepard Lunar-G Flights

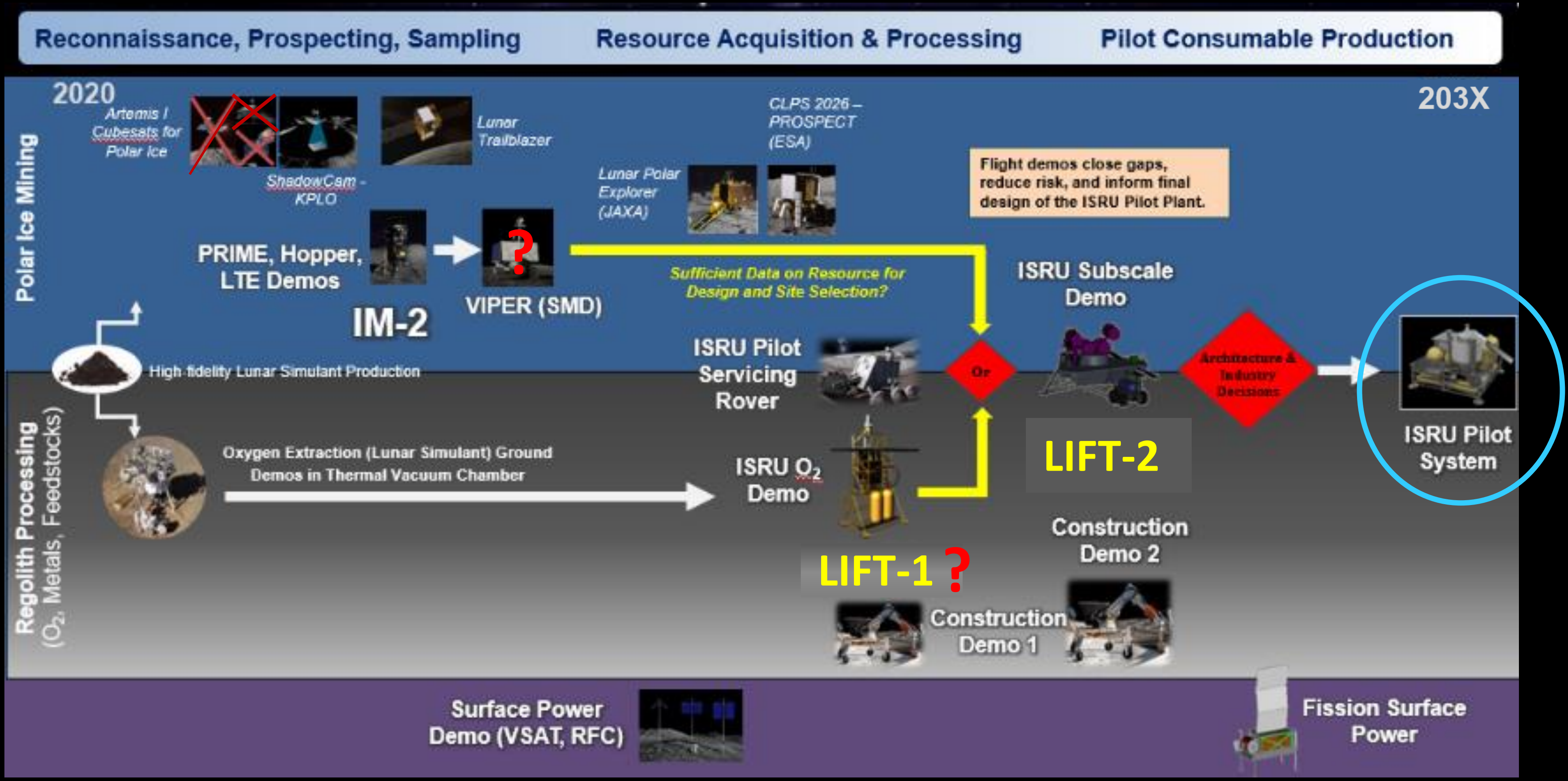
Flight Opportunities

- ✓ Lunar Regolith Characterization, Excavation & Transfer
- ✓ Oxygen Bubble

		T#	PI	LGA Technology	Lockers	Latest Acceptable Date	Notes
MANIFESTED	GCD	322	Sumlin	(Clothbot) Low-g Transport of Dust Liberated from Spacesuit Fabric	1		Erica M. staying on as PM for Cloth Bot until early spring.
MANIFESTED	GCD	315	Phillips	Electrostatic Dust Lofting	1		James (Jay) Phillips
MANIFESTED	GCD	316	Olsen	Electrodynamic Conveyor	1		
MANIFESTED	GCD	317	John	Hermes Lunar-G	1	End of FY 23	Erica Montbach leaving for new role SMD PESTO office. Flexible, but by end of FY 23 would be best. New PM is Fothergill, Jenna (KSC-UBG00) <jenna.fothergill@nasa.gov>
MANIFESTED	GCD	318	Edmunson	Duneflow	1	Flexible	
MANIFESTED	GCD	319	Mantovani	Vibratory Lunar Regolith Conveyor	2	TBD/But Flexible	With the vacuum chamber, the mass budget is a challenge.
MANIFESTED	GCD	320	Schuler	ISRU Pilot Excavator	1+1		
MANIFESTED	JPL	323	Anderson	Lunar Regolith Probe, Mechanical and Chemical (SPARTA Blue)	1	End of FY 23	Anything past FY23 will have an impact on schedule and budget. Bob is going to look more closely; but thought that 20K to get the students back and another 30K to pay for some of his time might be nessesary. We have to bear in mind that JPL funds are burdened, so 50K is likely the minimum.
MANIFESTED	JPL	321	Noel	Microfluidic Processing for Life Detection	1	End of FY 23	Aaron's interns and Andrew Berg will meet with Bob and Bob's students so they can collaborate as they build up their LGA payloads
MANIFESTED	GRC	324	Ferkul	Lunar Crew Fire Safety Research Observe flame front in lunar gravity	2		This team is pretty easygoing regarding the schedule. This technology is what they work on full time, so they feel like they can recover whenver needed.
MANIFESTED	UCSB	332	Naclerio	Root-Like Robots	2	Flexible	"Our payload will be complete by the original March 1st delivery date. We can easily shelf this project. The main challenge for us with the delay is that I will be leaving UCSB in June, however I can return for a few weeks whenever the launch ends up happening. Financially it might cost us on the order of $5,000. "
MANIFESTED	Honeybee	306	Zacny	LG Asteroid Soil Strength Evaluation Tool (ASSET)	1		Honeybee was able to make POCCETT fit into a single locker, which allowed us to add ASSET
MANIFESTED	Honeybee	348	Zacny	PUFFER-Oriented Compact Cleaning and Excavation Tool (POCCET)	1		Kris Zacny: "We will check internally and Bernice will respond if this new schedule should work (which I believe should not be a problem).
MANIFESTED	Honeybee	345	Williams	Honey Bubble Excitation Experiment (H-BEE)			Brought in through TechFlights
MANIFESTED	GCD	319	Mantovani	BACKUP Vibratory Lunar Regolith Conveyor	1	Flexible	BACKUP - The team had space parts and built up a single locker payload that could be substituted if a payload drops out.
BACKUP	GSFC	173	Robinson	Flow Boiling in Microgap Coolers (FBMC)	1		BACKUP - REFLIGHT

ISRU Path to Full Implementation & Usage*

*Proposed missions and timeline are contingent on NASA appropriations, technology advancement, and industry participation, partnerships, and objectives



Pilot Plant

Subscale End-to-End system:

- At scale to minimize/eliminate risk of scale up (~1 year; 1/10th scale for production)
- Demonstrate performance, wear, and maintenance
- Demonstrate key support infrastructure
- Understand processes and operations for subsequent responsible usage

- Dual Path that includes both Water Mining and Oxygen/Metal from Regolith
- Resource assessment missions to obtain critical data on mineral and water/volatile resources have started
  - Significant uncertainty if existing missions are sufficient to define resources for design and site selection

Questions?

Utilize CATALYSTS to Develop ISRU Technologies in Phases

Cross-Cutting Activities (Inclusive Innovation, NASA I-Corps, Center Call) and Other Tools

	NIAC	CIF / ECI	STRG	PCC	SBIR / STTR	ACO	TP	FO	T2
Name	NASA Innovative Advanced Concepts	Center Innovation Fund / Early Career Initiative	Space Technology Research Grants	Prizes, Challenges, and Crowdsourcing	Small Business Innovation Research / Small Business Technology Transfer	Announcement of Collaboration Opportunity	Tipping Point	Flight Opportunities	Technology Transfer
Program Overview	Nurture visionary ideas that could transform future NASA missions by engaging America's innovators and entrepreneurs as partners in the innovation journey.	Stimulate and encourage creativity and innovation within the NASA Centers and early career leaders.	Accelerate the development of low TRL space technologies to support future space science and exploration needs for NASA, OGAs, and the commercial space sector.	Conducts and promotes the use of prize competitions, challenges, and crowdsourcing activities to advance NASA's mission and enhance the agency's collaboration with the public.	Empowers small business communities to image, build, and utilize revolutionary technologies to drive NASA and the national economy to reach new heights.	Partners with U.S. companies to help advance industry capabilities that enable both Government and commercial missions.	Provides funding to U.S. companies to help advance promising technologies that enable both Government and commercial missions.	Rapidly demonstrates promising technologies for space exploration, discovery, and the expansion of space commerce through suborbital and hosted orbital testing with industry flight providers.	Ensures that innovations developed for exploration and discovery are broadly available to the public, maximizing the benefit to the Nation, and enabling spinoffs and commercial opportunities.
Target Participants	Government Academia Industry	NASA Internal	Academia	Academia Industry NASA Internal Public	Small Businesses Academia	Industry NASA Centers	Industry NASA Centers	Academia Industry NASA Centers	Industry NASA Internal
TRL	1-4	1-4	1-4	1-6	2-6	5-7	5-7	4-6	1-7

** FO is separate from ESIP during transition*