NASA In Situ Resource Utilization (ISRU)
Closer to Reality

XXIV Space Resources Roundtable (SRR)
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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.

HUMANS TO MARS

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

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Demonstrate & Utilize ISRU

HUMANS TO MARS

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Recap on ISRU Strategic Plan

Long-Term Vision

Scalable Space Mining production/utilization capabilities including sustainable commodities on the lunar & Mars surface*

Commercial Scale Water, Oxygen, Metals & Commodity Production

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

Commodities for Habitats & Food Production

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

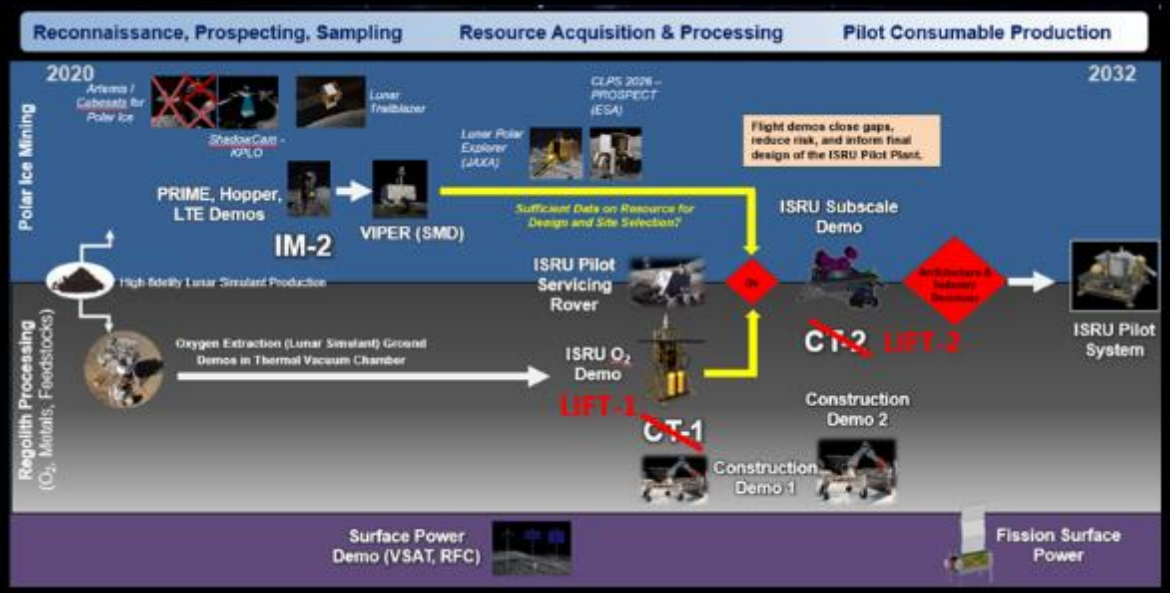
In Situ Derived Feedstock for Construction, Manufacturing, & Energy

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

Commodities for Commercial Reusable In-Space and Surface Transportation and Depots

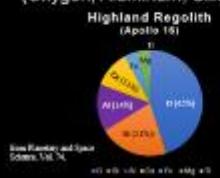
- 30 to 60 metric tons per lander mission
- 100's to 1000's metric tons per year of for Cis lunar Space
- 100's metric tons per year for human Mars transportation

Overarching Infusion Schedule

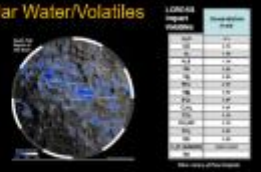


Time Phasing of Locations, Resources, and Products

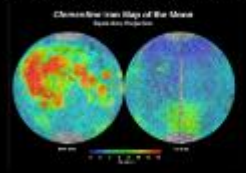
1. Polar Highland Regolith
(Oxygen, Aluminum, Silicon)



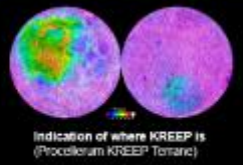
2. Polar Water/Volatiles



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



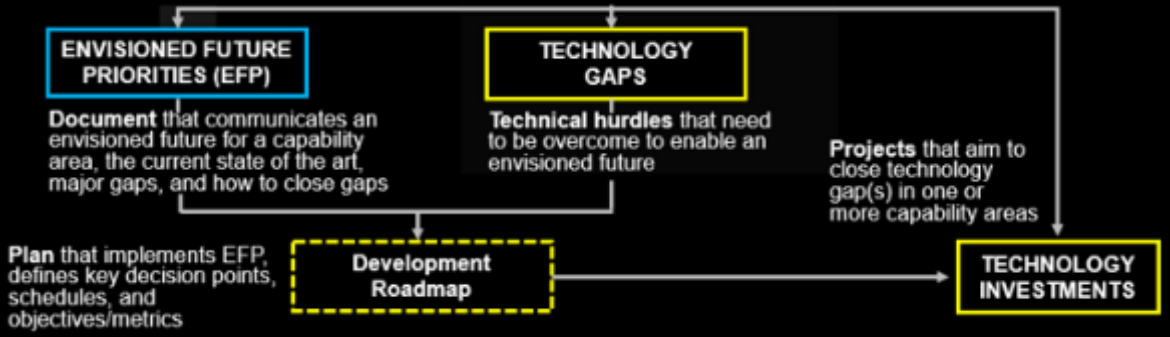
4. Rare Earth Elements & Thorium



Commodities

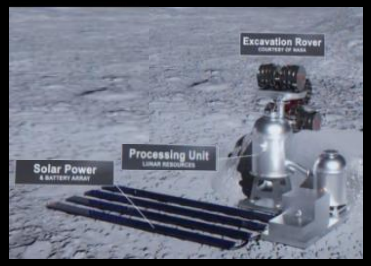
- Oxygen
- Water
- Bulk & Refined Regolith
- Raw & Refined Metals (Al, Fe, Ti)
- Silicon and Ceramics
- Construction Feedstock
- Manufacturing Feedstock
- Fuels, Plastics, Hydrocarbons
- Food/Nutrient Feedstock

Yearly Process to Evaluate & Update Plan



Technology & System Development Progress

- **Significant Funding and Advancement for Oxygen/Metal Extraction from Regolith**
  - **2 Technologies/Companies have made significant progress**
    - Carbothermal Reduction/Sierra Space
    - Molten Regolith Electrolysis/Lunar Resources
  - **Blue Origin received Tipping Point for MRE development**
  - **Other technologies/companies at lower TRL through SBIR, LuSTR, NSTGRO**



- **Limited Success to Date on Lunar Water Extraction Technologies**
  - **Subsurface heating and volatile removal has not worked to date (may be simulant related)**
  - **Water extraction reactor (JSC LADI) work cancelled before completion**
  - **Coring Auger/PVEx concept funded work completed before achieving TRL 5/6**
  - ➢ **Results from PRIME-1 and VIPER will be critical**

- **Significant Industry and International Interest in ISRU**
  - **Some companies working only with private investment: Cislune, Terraxis, Diatomic Space, Ethos Space**

- **New Shepard Lunar-g Flight Experiments Planned**
  - **5 Lunar Regolith Characterization, Excavation & Transfer experiments and 1 Oxygen Bubble experiment for MRE**

- **No Funded Mars ISRU At This Time**

- **ISRU System Modeling, Integration, and Testing**
  - **System Modeling & Analysis project started at the end of FY23**
  - **No funding yet for integrating hardware into systems and performing tests to achieve TRL 6**

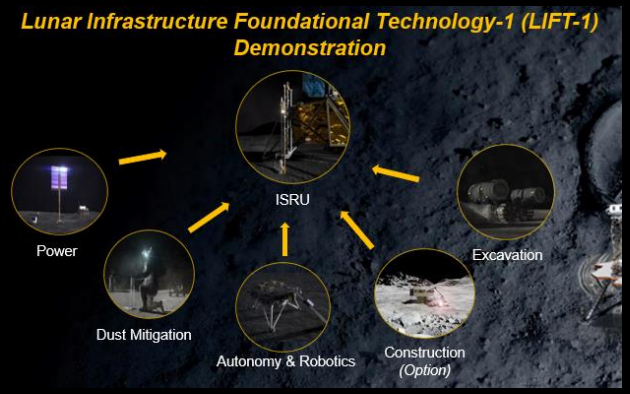
ISRU Flight Demonstration and Missions Progress

- **Cubsats for lunar resource mapping all failed**

- **PRIME-1 and VIPER missions for lunar polar water/volatile assessment are preparing for flight**
  - **Delays in missions will delay understanding of resources for subsequent technology development**
  - **No US follow-on to VIPER planned at this time**

- **ISRU Pilot Plant currently delayed to 2032/33 due to budget**
  - **Final dates for mission will depend on precursors demonstrations, industry involvement, and international partnerships**

- **Request for Information (RFI) released in Nov. 2023 for Lunar Infrastructure Fundamental Technology (LIFT)-1 mission with primary objective of oxygen generation from regolith**
  - **Review of submissions on-going**
  - **RFP release after STMD Shortfalls priority and budget are set**



- **Other STMD Funded Technologies could be useful for ISRU Resource Assessment missions**
  - **Sample and Regolith acquisition devices**
  - **Physical and mineral characterization instruments**
  - **Micro rovers and hopper**

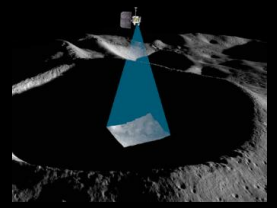
Overcoming Resource Uncertainty

On-going & Planned Missions Are a Good Start

Orbital

Lunar Reconnaissance Orbiter

Korean Pathfinder Lunar Orbiter (KPLO) & ShadowCam



Artemis I Cubesats

Lunar Trailblazer

Surface – Ground Truth

PRIME-1

VIPER

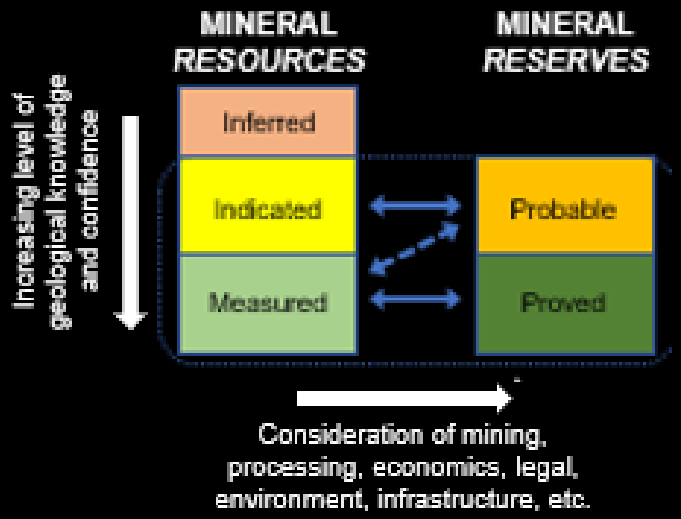
PROSPECT - ESA

LUPEX - JAXA

China:
Chang'e 7, 8

Russia:
Luna 26, 27

A Coordinated International Lunar Resource Campaign is Needed



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.

IAC-22,D3,1,14,x73338

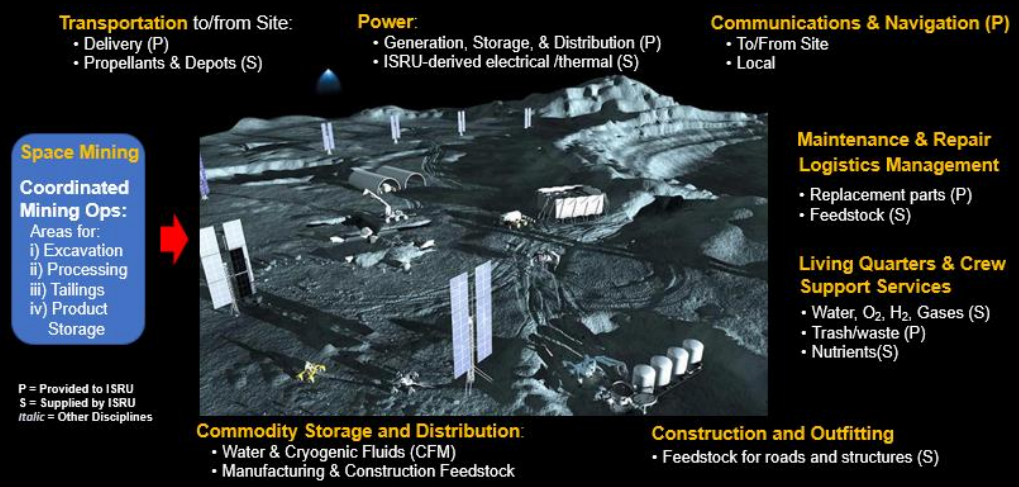
The Moon Needs an International Lunar Resource Prospecting Campaign

Clive R. Neal[a*], Antonino Salmeri[b], Angel Abbud-Madrid[c], James D. Carpenter[d], Anthony Colaprete[e], Karl A. Hibbitts[f], Julie Kleinhenz[g], Mathias Link[h], Gerald Sanders[i]

- A coordinated no-obligation campaign for lunar polar resource *science* was addressed by the International Space Exploration coordination Group (ISECG)
- Several studies and workshops have been held on the subject: LWIMS, LEAG Volatiles SAT, LSSW-17 & 18
- A new lunar polar resource campaign strategy is needed that enables understanding of resource *RESERVES* not just science
- NASA Tiger Team initiated by Federated Board to address question of NASA need and responsibility for lunar water resource exploration

Advancing ISRU in Artemis and the Cis-Lunar Economy

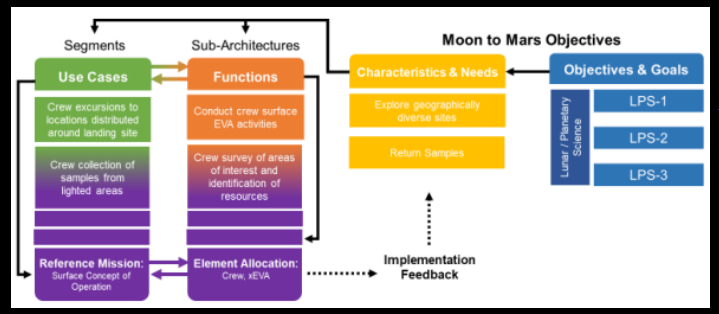
Establishing Support Infrastructure



- **Working with Lunar Architecture Team and Lunar Site Planning & Design Team on ISRU and infrastructure placement**
- **Working with Lunar Surface Innovation Consortium (LSIC) and internal NASA on support infrastructure needed for 'Large' scale ISRU**
- **Significant NASA and Private Investments in Infrastructure:** Transportation, Power, Mobility Platforms, Robotics & Automation, Communication Relay, High Speed Computers, In Space Manufacturing, and Surface Construction

ISRU in the Artemis Campaign

*Example of Mapping Approach in ADD**



Moon to Mars Objectives for Resource Exploration, ISRU, Responsible Usage

ISRU is a Sub-Architecture

Characteristics & Needs formulated for ISRU for Foundational Exploration Segment

In-Situ Resource Utilization Systems	The group of capabilities dealing with estimating resource reserves and harvesting these resources to generate products (e.g., consumables, feedstocks for manufacturing and construction) on other planetary bodies (the Moon, Mars, etc.) or environments to further the goals of a project or mission while reducing the reliance on Earth-based resources and make space missions more sustainable and cost-effective.

- **Strategic Analysis Cycles (SAC24)**
  - **Objective Decomposition: Capability/Need, Use Cases, & Functions started**
  - **Significant number of Lunar and Mars tasks with direct (5) or indirect ISRU (11) involvement**
  - **SMD-STMD-ESDMD Tiger Team on Lunar Resource Assessment – Reserve Characterization**
  - **Looking ahead to defining Lunar Sustainability Segment of Artemis ADD**
- **DARPA LunA-10**
  - **DARPA led lunar commercial & infrastructure architecture study.**
  - **Initial results presented at LSIC Spring Meeting and Final report in June 2024**

**2003 Moon to Mars Architecture Definition Document, (ESDMD-001) Rev A.*

ISRU Partnership and Collaboration Progress

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

International Agencies*

JAXA, esa, ISA, ASI Agenzia Spaziale Italiana, Canadian Space Agency / Agence spatiale canadienne, LSA Luxembourg Space Agency, DLR, Australian Space Agency, CSIRO, KIGAM, KICT

Public-Private Partnerships*

BLUE ORIGIN, SIERRA SPACE, LUNAR RESOURCES

- Tipping Points/ACOs
- Private investment is growing in ISRU
- Centers partnerships encouraged in new work

Applicability to Terrestrial Mining & Markets

AROSE, USGS, CATERPILLAR, ELECTRIC MINE CONSORTIUM, Lunar Outpost, METALYSIS, OFFWORLD, HELIOS

Consortiums

(To Promote Development, Standards, Interfaces, etc.)

Lunar Surface Innovation Consortium, esric, LEAG (Lunar Exploration Analysis Group)

Commercial Advisory Board (CAB)

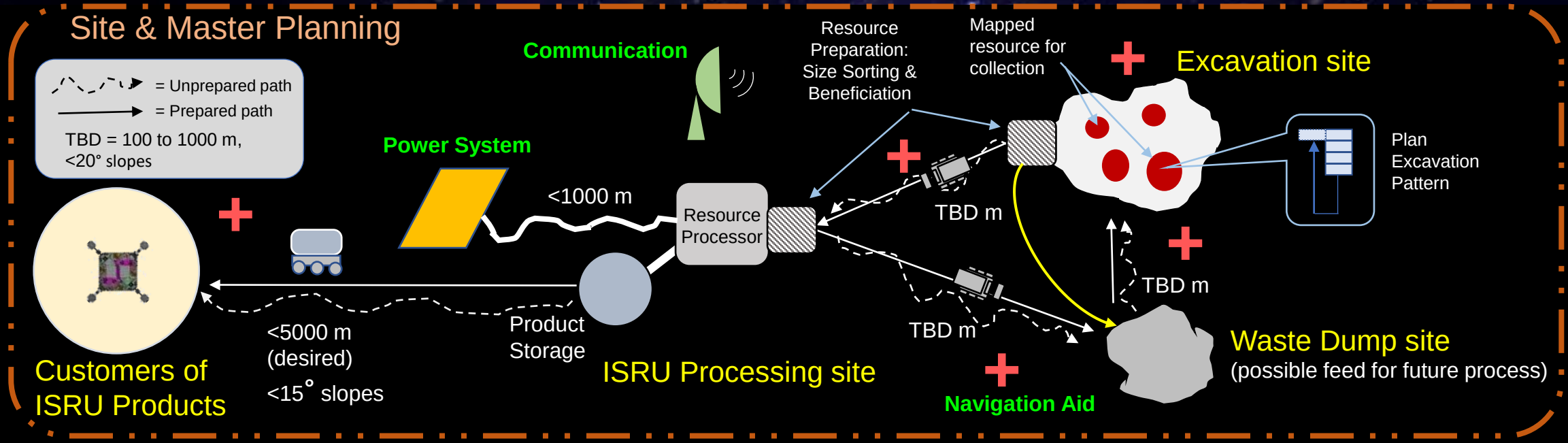
LOGIC – Lunar Operating Guidelines for Infrastructure Consortium

COSMIC – Consortium for Space Mobility and ISAM Capabilities

DARPA

LunA-10 – 10-year Lunar Architecture

Efforts are Underway to Better Align Lunar and Terrestrial Industies



Areas of Commonality with Terrestrial Mining to Achieve the 'Mine of the Future'

Resource Assessment – Mapping – Valuation

1. High confidence in resource reserves

Infrastructure for Mining and Processing

2. Continuous renewable power at multiple and remote locations
3. High accuracy positioning, navigation, and timing (PNT) in non-GPS environment
4. Secure, distributed, high bandwidth communication network
5. Rugged on-board processing and Edge computing

Operations for Mining and Processing

6. Data rich environment with real-time measurements
7. High level of autonomy for all operations
8. Minimize logistics and ease maintenance/On-site manufacturing
9. Electrification of all mechanisms and platforms

Safety

10. Minimize on-site human/crew involvement, esp. high-risk operations
11. Minimize number and severity of safety and time critical operations

Environmental Impact

12. Minimize release/exposure of corrosive/hazardous reagents and fluids to crew/space suits and environment
13. Mitigate environment impacts on hardware/operations and vice versa
14. Continuously and distributed environmental monitoring
15. Remediate sites at completion of operations

Presentation Take-Ways – *ISRU is Getting Closer to Reality*

- **NASA ISRU has established Strategic plans, objectives, gaps, priorities – With process to update**
- **Significant progress has been made in developing Lunar ISRU technologies**
  - We are about to start building and testing systems
  - We need to establish frameworks for requirements, interfaces, integration, and testing to promote industry and international involvement
- **Progress is being made on ISRU Missions**
  - Ground truth missions (PRIME-1 & VIPER)
  - LIFT-1 RFI
- **Progress is being made on advancing the Cis-Lunar Ecosystem**
  - Work is going on within NASA and the community at large on how ISRU fits into the Artemis program and what is needed to establish the supporting infrastructure and cis-lunar ecosystem
  - There are significant government, industry, and consortium efforts to develop and reduce the risk on the Supply side; Still need to develop and incentivize the markets
  - Public-Private Partnerships and applicability to Terrestrial markets and needs are critical

Thank You. Questions?

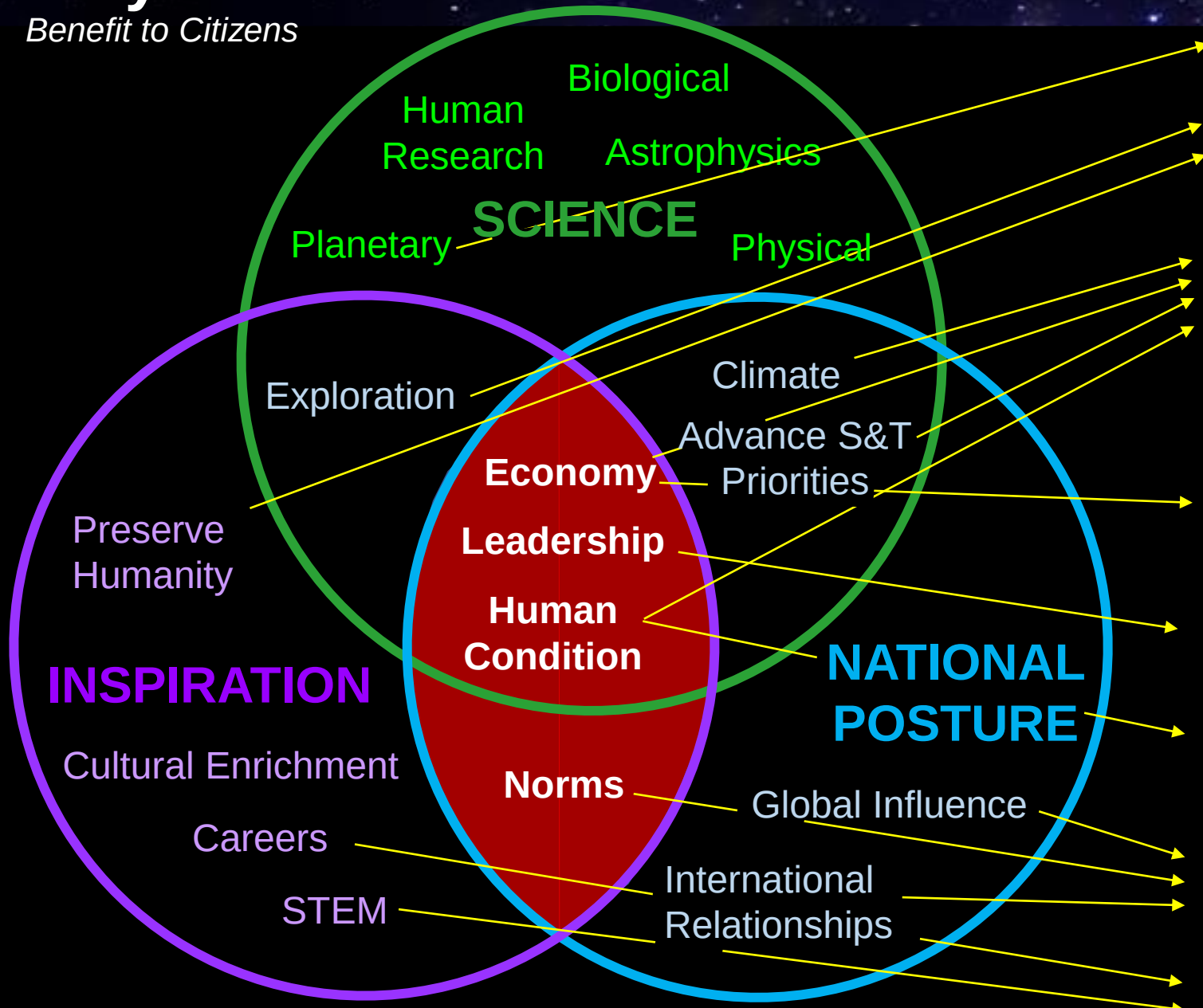
ISRU Envisioned Future Priorities at:
https://techport.nasa.gov/framework

Backup

Why Go?

Benefit to Citizens

Ties to Space Resource Utilization



Resources and Science

Enhanced Mission Capabilities & Becoming Self Sufficient in Space

Terrestrial & Environmental Benefits

- Renewable Energy/CO_2 Reduction, Recycling/Repurposing, Water cleanup, Environmentally-friendly Mining and Construction

Space Commercialization: Propellants, Metals, Construction, Power …

- Spin-in/Spin-out w/ Terrestrial Industry

US/NASA is charting the course in ISRU

Enhanced Radiation Shielding, Large Internal Volume for constructed Habitats

Norms and Policy for Space Mining and Commerce

Requires Diverse Technical Disciplines

The ‘Economics’ of ISRU

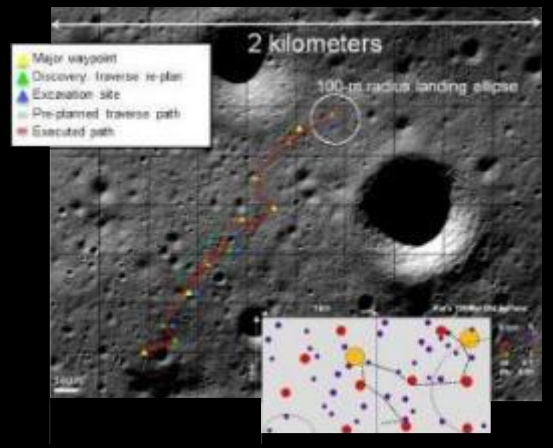
The Economics of ISRU/space resources depends on the Location and Amount/Distribution of the Resource, the Infrastructure and Difficulty of ISRU, and the Amount/Frequency of the Product

Location

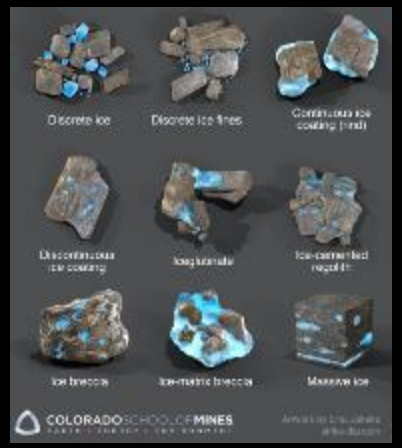
- Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
- Resource must be within ‘reasonable’ distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.
- Product produced must be within ‘reasonable’ transportation distance of user: Transportation of product to ‘Market’ must be considered

Resource Must Be Known

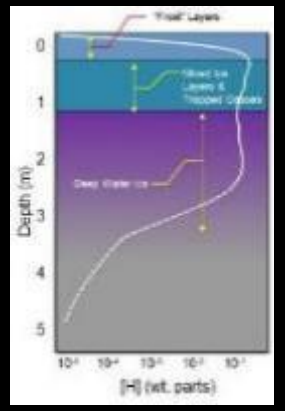
Need to Evaluate Local Region (1 to 5 km)



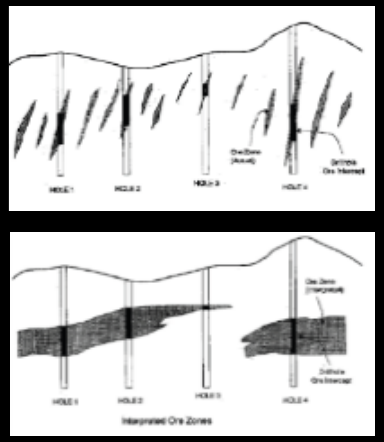
Need to Determine Form



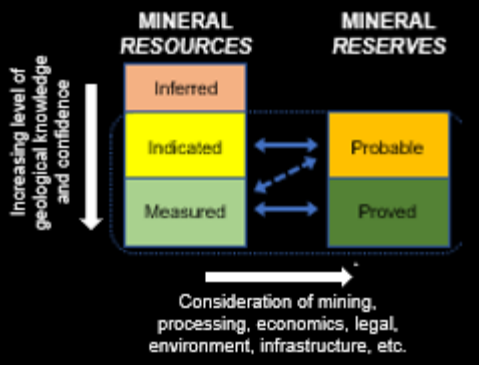
Need to Determine Vertical Profile



Need to Determine Distribution



Resources vs Reserves



Infrastructure and Difficulty of ISRU:

- Mass ROI - mass of equipment and unique infrastructure compared to bringing product and support equipment from Earth.
- Cost ROI - cost of development and certification of equipment and infrastructure compared to elimination of launch costs or reuse of assets (e
- Time ROI time required to notice impact of using product use compared to Earth delivered product
- Mission/Crew Safety ROI - increased safety of product compared to limitations of delivering product from Earth

Amount/Frequency of product needed must justify investment in extraction and processing

- Requires long-term view of exploration and commercialization strategy to maximize benefits: mass/year product vs mass of Infrastructure

15

NASA STMD LIFT-1 Lunar Demonstration

STMD anticipates releasing a **RFI in late 2023** to obtain feedback and gauge interest from industry for a LIFT-1 demonstration RFP Solicitation

Lunar Infrastructure Foundational Technology-1 (LIFT-1) Demonstration

ISRU

Power

Dust Mitigation

Autonomy & Robotics

Construction *(Option)*

Excavation

Lunar lander will be competed

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

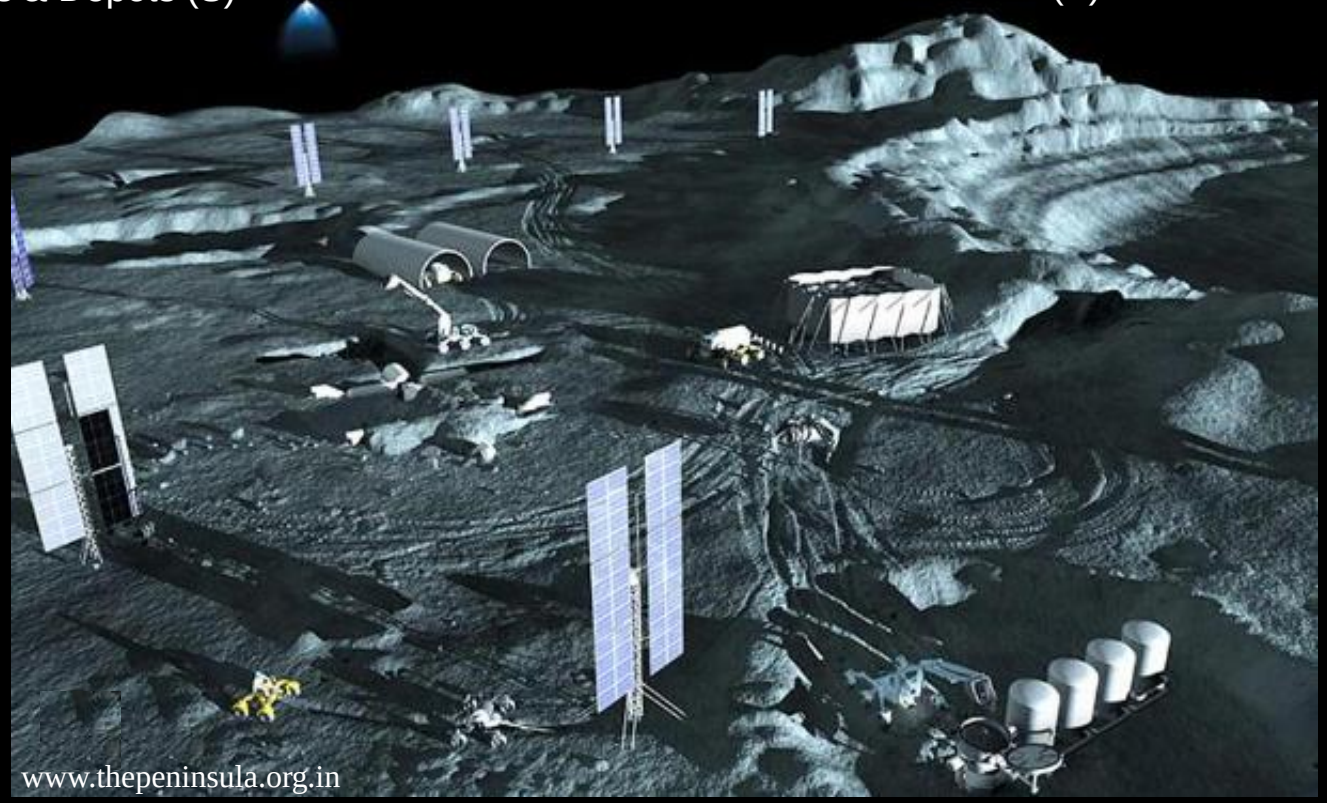
Transportation to/from Site:
- Delivery (P)
- Propellants & Depots (S)

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)