EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

In-Situ Resource Utilization (ISRU) Overview

Presentation to NASA Advisory Council (NAC) Technology Innovation, and Engineering Committee

May 15, 2023

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In-Situ Resource Utilization (ISRU)

Using space-based resources for deep space exploration

Traditional examples of ISRU

- Extracting volatiles from soil for consumption, hygiene, propulsion
- Using soil/regolith for construction materials

Benefits of ISRU

- ISRU can reduce mission and architecture mass and costs; Enables fewer launches to get supplies to our destination – propellant, consumables, construction materials, etc.
- ISRU can increase safety for crew and enhance mission capabilities, allowing us to explore farther from Earth with more independence.
- Learning to use space resources can help us on Earth
- Planetary preservation is important in responsibly using space resources.

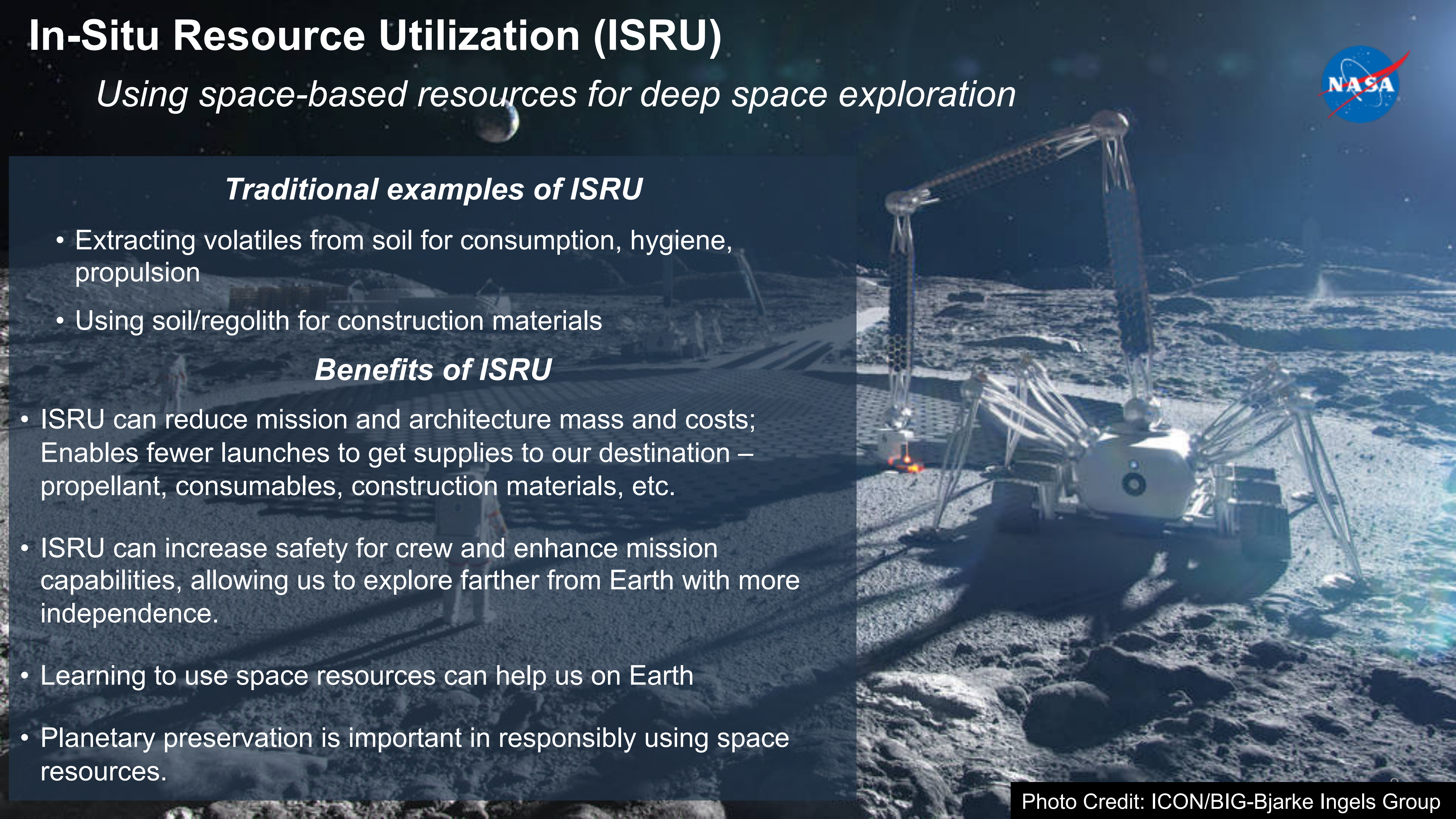


Photo Credit: ICON/BIG-Bjarke Ingels Group

Lunar Surface Innovation Initiative (LSII)

Works across industry, academia, and government to develop transformative capabilities for lunar surface exploration.

In-Situ Resource Utilization (ISRU)

The collection, processing & use of in-situ materials for production of consumables such as oxygen or propellant.

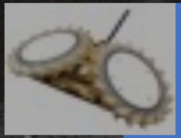
Excavation and Construction

Enables autonomous excavation of in-situ materials for construction of structures such as landing pads, habitats, etc.

Surface Power

Technologies that can provide continuous power throughout the lunar day and night.

Lunar Surface Infrastructure

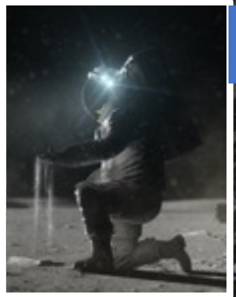


Extreme Environments

Enables operations across the full range of lunar surface conditions.

Extreme Access

Enables humans/robotic systems to access, navigate, assess, and explore previously inaccessible locations on the lunar surface.



Dust Mitigation

Active, passive & operational technologies to remediate lunar dust hazards.

Lunar Surface Technology Demonstration Strategy

ISRU, Power, Autonomy, Robotics, Excavation, Construction

Early lunar surface demonstrations will increase technology readiness for key infrastructure capabilities with opportunities for collaboration with OGAs, industry, academia, and international partners

Oxygen Extraction
Ground Demo

◆ IM-2 Demo (on CLPS IDIQ)

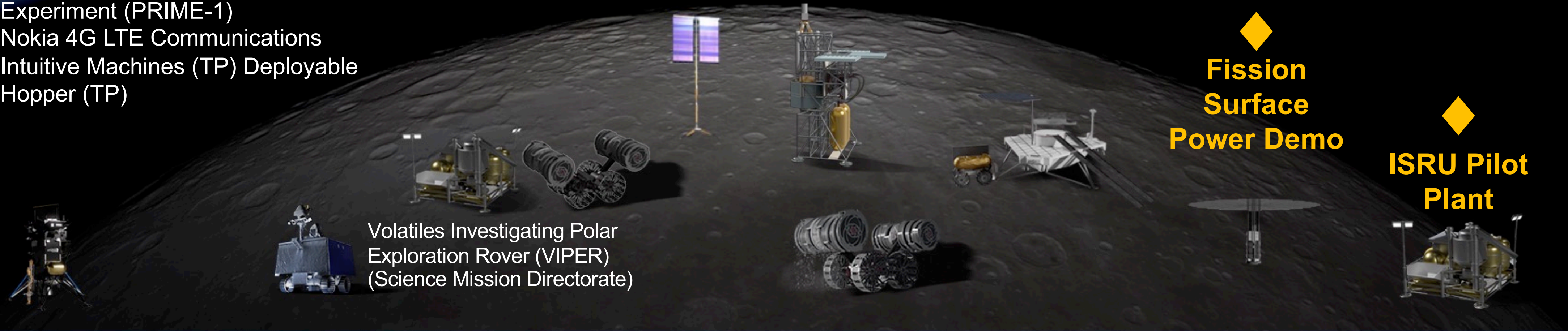
- Polar Resources Ice Mining Experiment (PRIME-1)
- Nokia 4G LTE Communications
- Intuitive Machines (TP) Deployable Hopper (TP)

◆ CT-1 Space Tech CLPS Demo

◆ CT-2 Space Tech CLPS Demo

CT Candidate Technologies (in formulation):

- ISRU Subscale Demo
- Power (e.g. Vertical Solar Array, Power Beaming, Fuel Cells)
- Dust Mitigation
- Autonomy & Robotics (e.g. Mobility, Navigation, etc.)
- Excavation
- Construction



Volatiles Investigating Polar Exploration Rover (VIPER) (Science Mission Directorate)

◆ Fission Surface Power Demo

◆ ISRU Pilot Plant

◆ Space Tech Lunar Surface Demo

2023

2033

TP Tipping Point

Lunar Surface Innovation Consortium (LSIC)

Done

Facilitated by Johns Hopkins APL, LSIC is a nationwide alliance of universities, industry, non-profits, NASA, and other government agencies with a vested interest in establishing a sustained presence on the Moon. LSIC engages the community through bi-annual meetings, monthly capability focus groups, and themed technical workshops.

7 Bi-annual meetings


Lunar Simulant Assessment

POWER SYSTEM REPORT: TECHNOLOGY DEVELOPMENT STATUS AND MATURATION ASSESSMENT

6 Focus groups


SEMI-ANNUAL MEETING REPORT:

Lunar Surface Innovation Consortium Fall Meeting 2022

Surface Power Home

In Situ Resource Utilization Home

~800 Organizations working toward one goal


LSII | ISRU Industry Supply and Demand Workshop

LSIC | Dust Mitigation Workshop

LSIC | Workshop on Lunar Mapping for Precision Landing

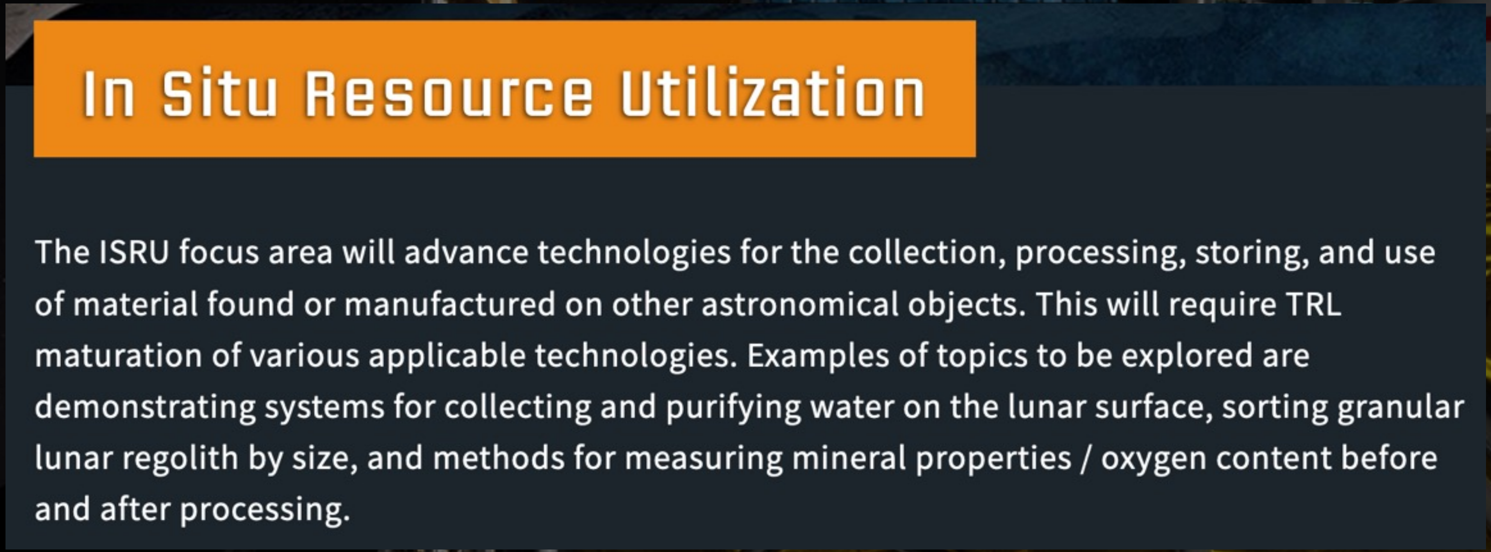
1700 People attended 8 thematic workshops

APL Lunar Surface Innovation Consortium

For more information: www.lsic.jhuapl.edu

LSIC ISRU Focus Group

- Monthly ISRU Focus Groups enable regular communication across NASA and broad external communities.
  - Currently includes ~200 participants from across industry, academia, government, and international entities.
- Identifies key objectives and sub-groups, which include:
  - O2 and Metal
  - Water Ice-prospecting and Minining
  - Value Networking
  - Modular Interoperability
- APL synthesizes data and feedback from NASA and external stakeholders for inclusion in annual ISRU Technology Assessment.



In Situ Resource Utilization

The ISRU focus area will advance technologies for the collection, processing, storing, and use of material found or manufactured on other astronomical objects. This will require TRL maturation of various applicable technologies. Examples of topics to be explored are demonstrating systems for collecting and purifying water on the lunar surface, sorting granular lunar regolith by size, and methods for measuring mineral properties / oxygen content before and after processing.

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In Situ Resource Utilization (ISRU) Strategy - Scope, Plans, and Priorities

Presentation to NASA Advisory Council (NAC) Technology Innovation, and Engineering Committee

May 15, 2023

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LIVE: Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities

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

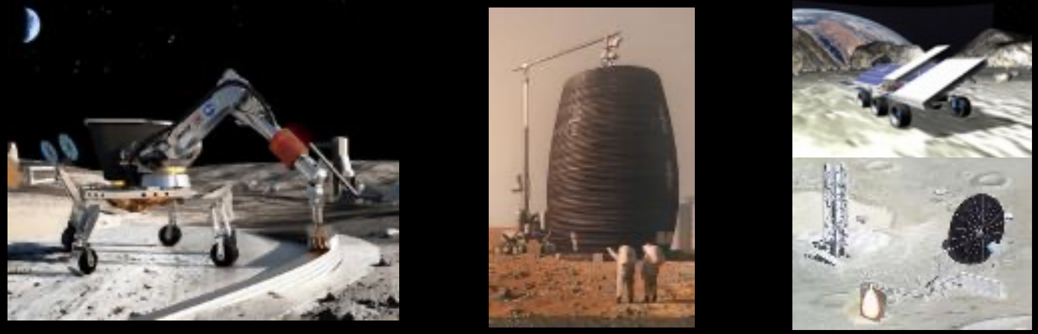
COMMERCIAL SCALE WATER, OXYGEN, METALS & COMMODITY PRODUCTION

- 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

All activities depicted not currently funded or approved. Depicts "notional future" to guide technology vision.

*Commodities are items and consumables that can be eventually sold

ISRU Must Operate as Part of A Larger Architecture

P Provided to ISRU
S Supplied by ISRU
Italic Other Disciplines

- Architecture elements must be designed with ISRU product usage in mind from the start to maximize benefits
- Infrastructure capabilities and interdependencies must be established and evolve with ISRU product users and needs
  - Transition from Earth-supplied to ISRU-supplied
  - Guided by overarching Site Master Plan

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

Advanced Power Systems

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

Advanced Propulsion
Entry Descent and Landing

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

Adv. Communication & Navigation

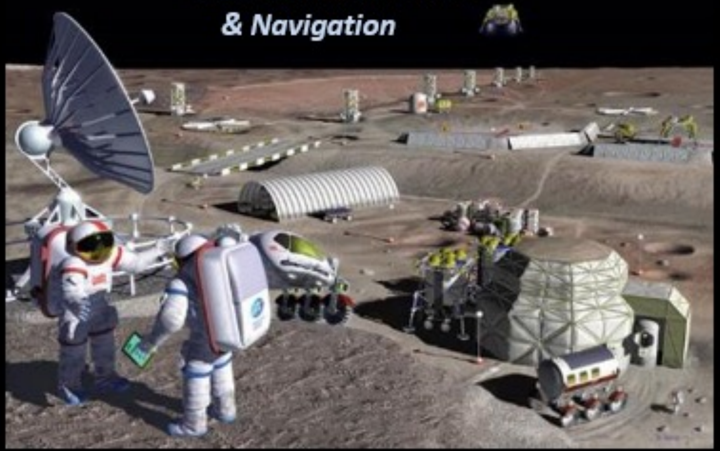
Maintenance & Repair

Logistics Management
- Replacement parts (P)
- Feedstock (S)

In Space/Surface Manufacturing

ISRU

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

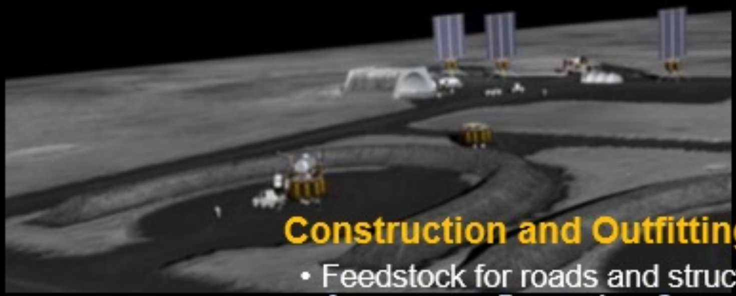


In situ Instruments/Sensors
Autonomous Systems
Adv. Thermal Management

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

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

Cryogenic Fluid Management
Autonomous Systems & Robotics
Autonomous Excavation, Construction, & Outfitting



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

Autonomous Excavation, Construction, & Outfitting
Autonomous Systems & Robotics

In Situ Resource Utilization (ISRU) Capability – *‘Prospect to Product’*

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

Destination Reconnaissance & Resource Assessment

Assessment and mapping of physical, mineral, chemical, and water/volatile resources, terrain, geology, and environment

Resource Acquisition, Isolation, & Preparation

Atmosphere constituent collection, and soil/material collection via drilling, excavation, transfer, and/or manipulation before Processing

Resource Processing

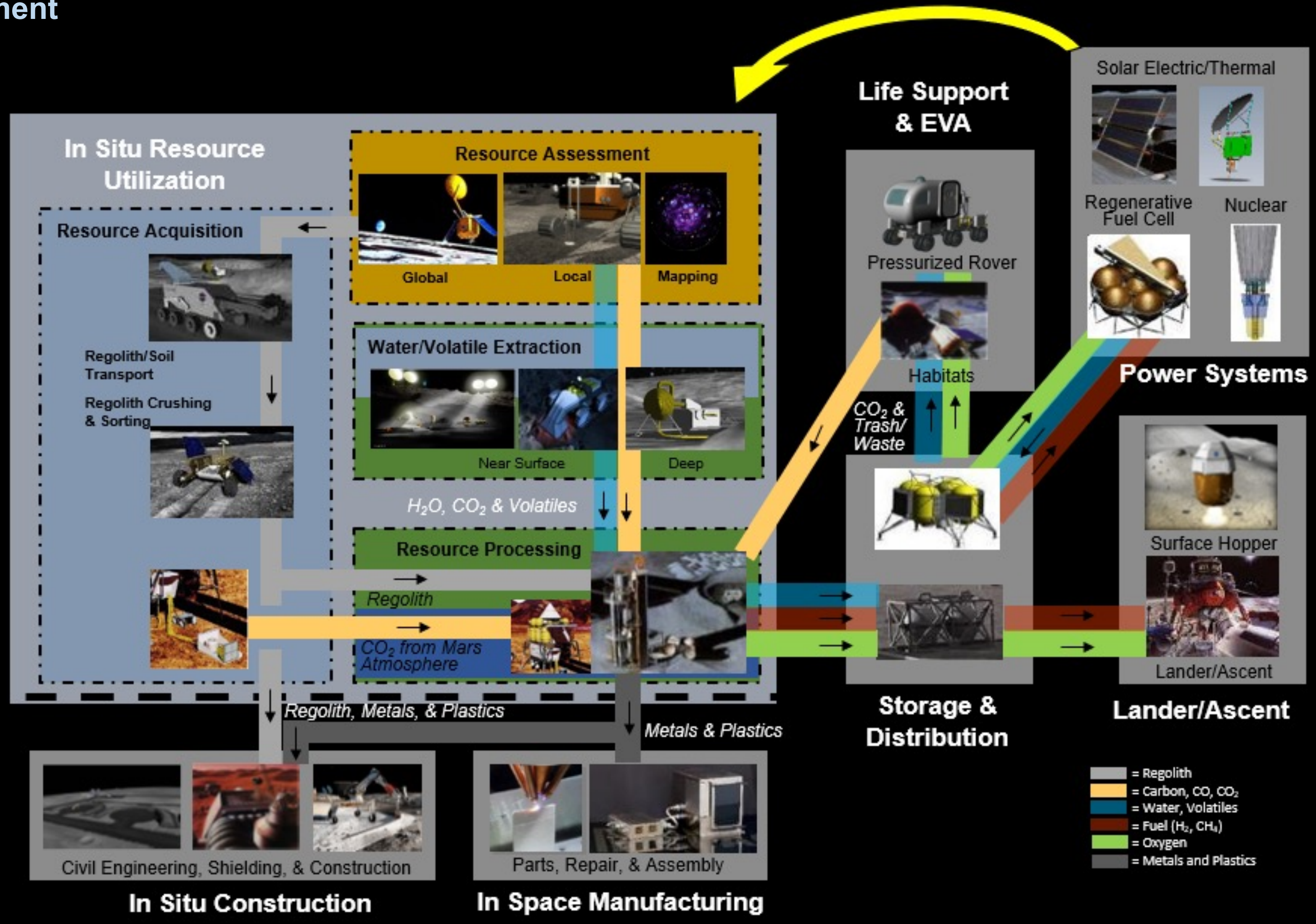
Chemical, thermal, electrical, and or biological conversion of acquired resources and intermediate products into

- Mission Consumables
- Feedstock for Construction & Manufacturing

Water/Volatile Extraction

A subset of both Resource Acquisition and Processing focused on water and other volatiles that exist in extraterrestrial soils

- **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**

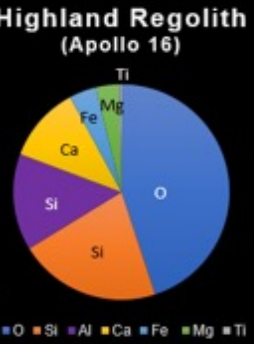


*Commodities are items and consumables that can be eventually sold

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

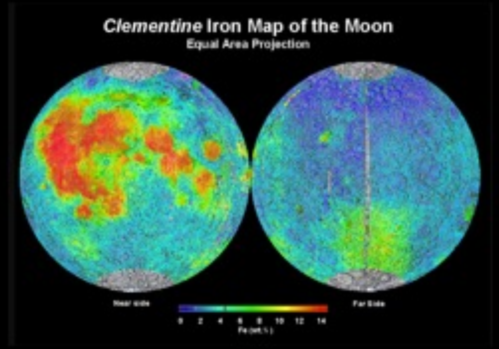
- ISRU starts with the easiest resources to mine, requiring the minimum infrastructure, and providing immediate local usage
- The initial focus is on the lunar South Pole region (highland regolith and water/volatiles in shadowed regions)
  - ISRU will evolve to other locations, more specific minerals,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

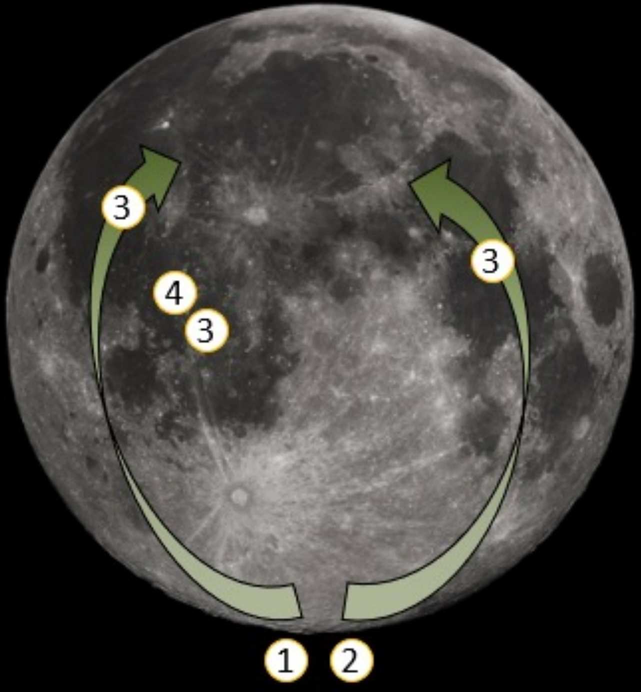
1. Polar Highland Regolith
(Oxygen, Aluminum, Silicon)



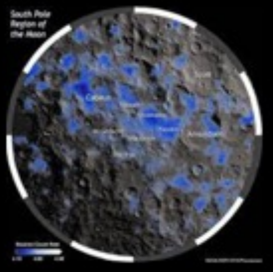
from Planetary and Space Science, Vol. 74,

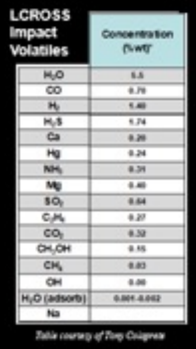
3. Ilmenite and Pyroclastic Glass
(Iron, Titanium, Solar Wind Volatiles)





2. Polar Water/Volatiles

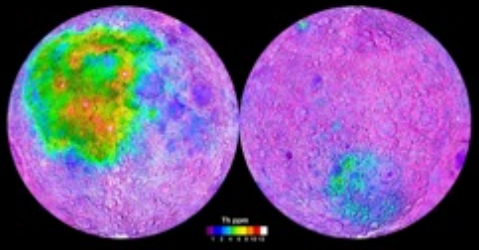




LCROSS Impact Volatiles	Concentration (%wt)
H_2O	5.5
CO	0.70
H_2	1.40
H_2S	1.74
Ca	0.20
Hg	0.24
NH_3	0.31
Mg	0.40
SO_2	0.64
C_2H_4	0.27
CO_2	0.32
CH_3OH	0.15
CH_4	0.03
OH	0.00
H_2O (adsorb)	0.001-0.002
Na	

Table courtesy of Tony Colaprete

4. Rare Earth Elements & Thorium



Indication of where KREEP is
(Procellerum KREEP Terrane)

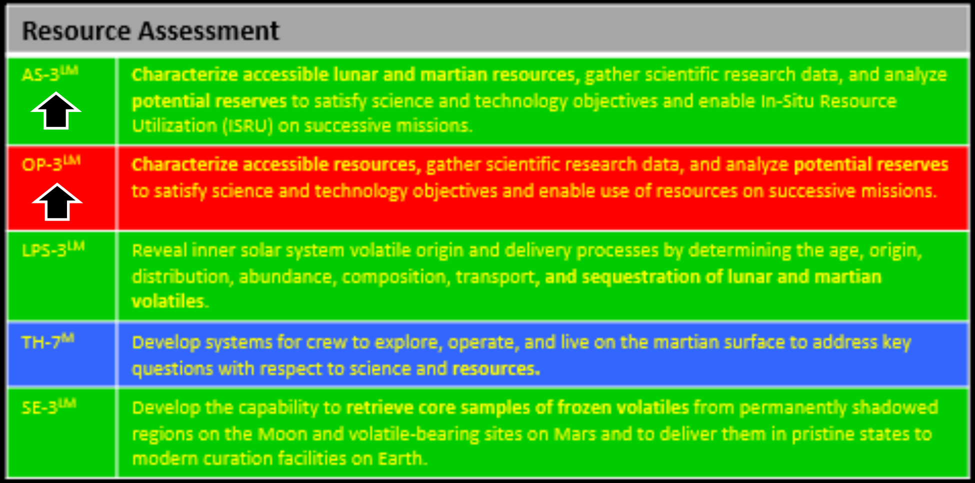
Commodities

- 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

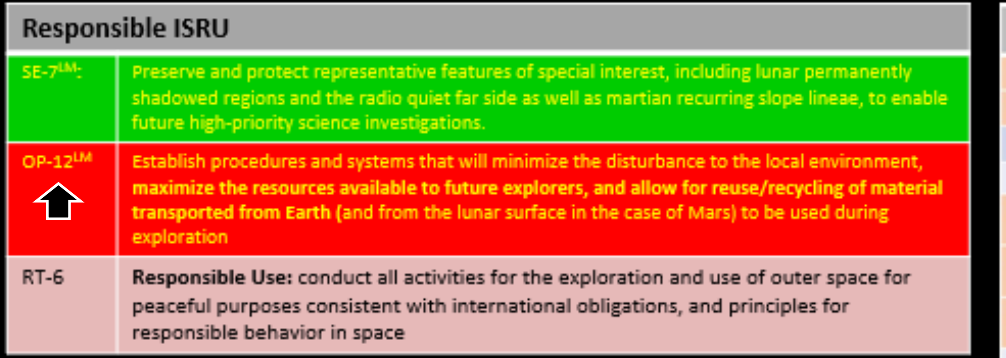
Moon to Mars (M2M) Blueprint Objectives and ISRU

- NASA Moon to Mars (M2M) Blueprint Objectives officially released in Sept. 2022 at IAC
- A significant number of objectives align with ISRU in three general areas (Resource Assessment, ISRU and Usage, and Responsible ISRU)
- A significant number of Recuring Tenets are achieved with ISRU development and implementation

➢ **Current Artemis Plan is focused on Human Lunar Return and Foundational Lunar Exploration phases**

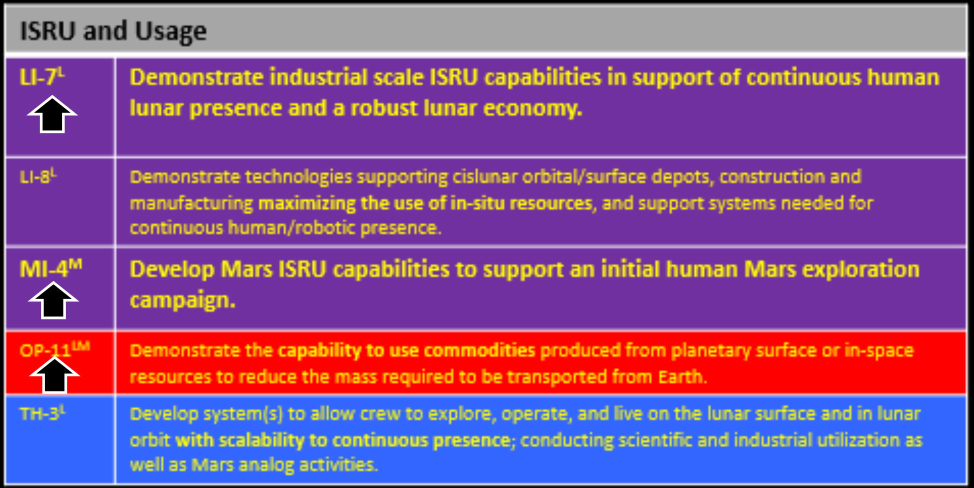


Resource Assessment	
AS-3^{LM} ⬆	**Characterize accessible lunar and martian resources**, gather scientific research data, and analyze **potential reserves** to satisfy science and technology objectives and enable In-Situ Resource Utilization (ISRU) on successive missions.
OP-3^{LM} ⬆	**Characterize 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.

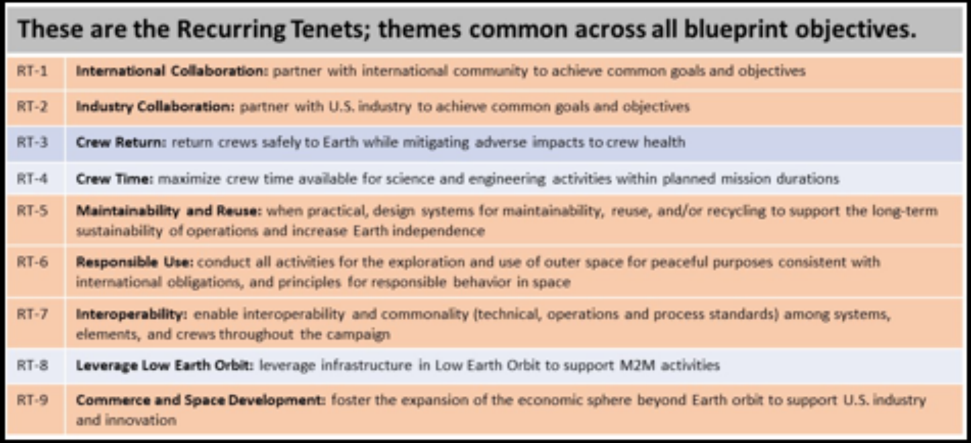


Responsible ISRU	
SE-7^{LM}:	Preserve and protect representative features of special interest, including lunar permanently shadowed regions and the radio quiet far side as well as martian recurring slope lineae, to enable future high-priority science investigations.
OP-12^{LM} ⬆	Establish procedures 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
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

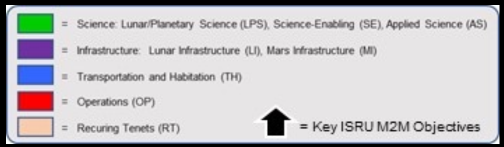
Superscript text indicates the applicability to Lunar (L), Martian (M) or both (LM).



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} ⬆	**Develop 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.

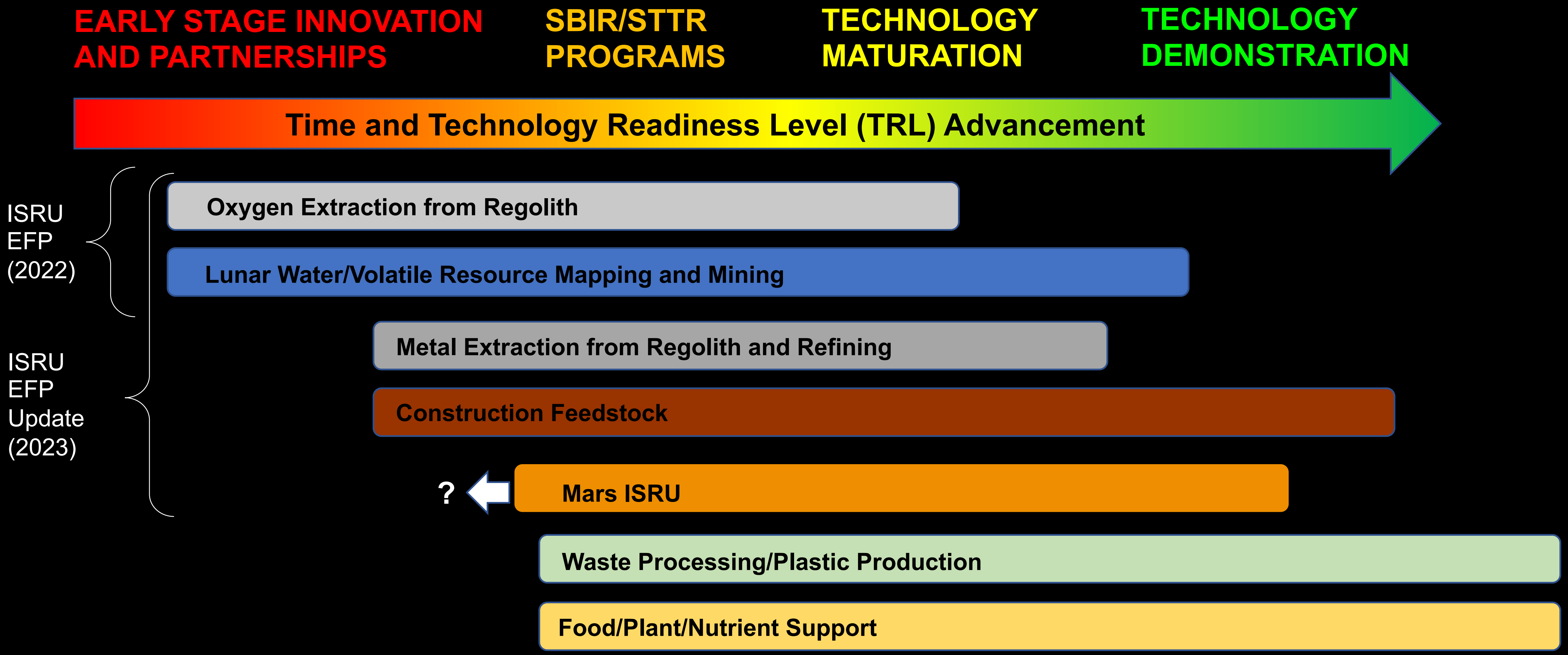


These are the Recurring Tenets; themes common across all blueprint objectives.	
RT-1	**International Collaboration:** partner with international community to achieve common goals and objectives
RT-2	**Industry Collaboration:** partner with U.S. industry to achieve common goals and objectives
RT-3	**Crew 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)
🟧 = Recuring Tenets (RT)
⬆ = Key ISRU M2M Objectives

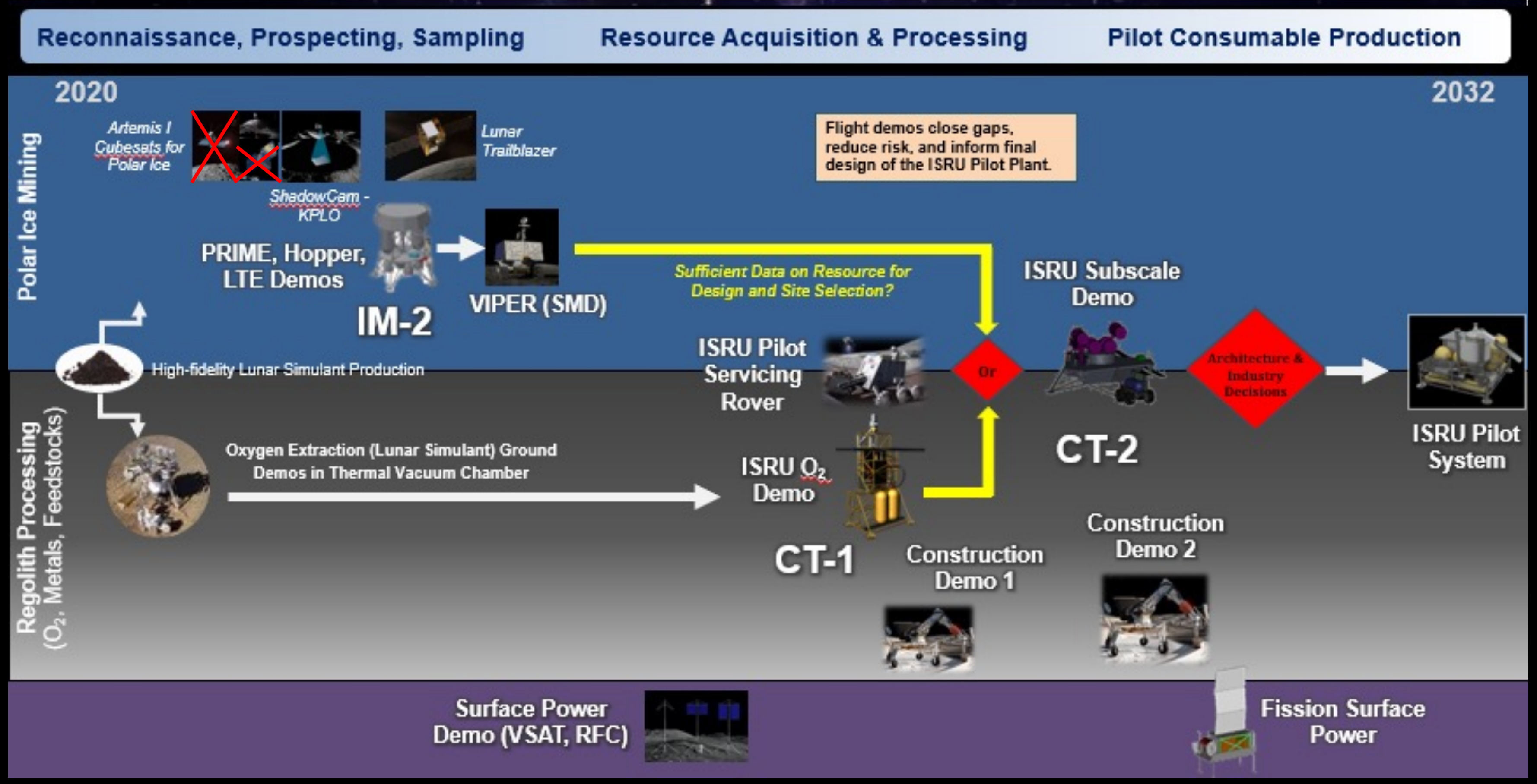
Multiple Areas of ISRU under Development in Phases



- Utilize STMD solicitations and internal work to progress ISRU work areas as TRL progresses
- Initial Focus was on Oxygen Extraction and Water Mining.
  - Now that they have progressed, earlier TRL solicitations moved to next phase of work (Metals and Construction Feedstock) and evaluate specific gaps or next gen high risk/high payoff concepts

ISRU Path to Full Implementation & Commercialization*

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



Full-scale implementation & Commercial Operations

LI-7^{L}	**Demonstrate industrial scale ISRU capabilities in support of continuous human lunar presence and a robust lunar economy.**
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.

Beyond 2032 Not Defined

Requires transition and 'Pull' from STMD to ESDMD and Industry

- Dual Path that includes both Water Mining and Oxygen/Metal from Regolith
  - Regolith Processing and O_2/Metal Path supports Surface Construction activities and demonstrations as well
- Ground development of multiple critical technologies in both pathways underway to maximize success and industry involvement
- 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

Plan to Achieve ISRU Outcome

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**
  - Define Initial and Long-term Customer Needs for ISRU-derived Products
    - Work inside and outside of NASA to define near-term needs and to lay the foundation for long-term lunar economic development

  - Advance ISRU technologies and systems for lunar missions by utilizing NASA solicitations, public private partnerships, internal/external investments
    - Perform and support extensive ground development, low/micro-g flights, and integration/testing of hardware and systems
    - Coordinate requirements, development, and implementation of infrastructure required for ISRU operations (Power, Product Storage, Comm & Nav., Excavation and Construction, etc.)

  - Reduce Risk and Promote Investment in ISRU Systems and Products
    - NASA/Government provide to industry key and enabling capabilities and resources to include:
      - Perform fundamental research and technology development, both high TRL (near term) and low TRL (distant)
      - Information, facilities, and technologies (technology transfer)
      - Foster and support or lead system modeling/analysis, integration, and analog and environmental testing of diverse technologies from multiple companies and partners
    - 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)

- **Promote Industry-led ISRU Development thru End-to-End ISRU Production of Commodities (i.e. Pilot Plant)**
  - Production at sufficient scale to eliminate risk of Full-scale system
  - Initially use ISRU-derived commodity in non-mission critical applications (life support, hopper propellant, etc.)

- **ISRU must be demonstrated on the Moon before mission-critical applications are flown**
  - Utilize lunar flight demonstrations and Pilot Plant operations to break 'chicken and egg' cycle
  - Conduct prospecting missions to locate predicted water/ice reserves proximal to potential base camps.

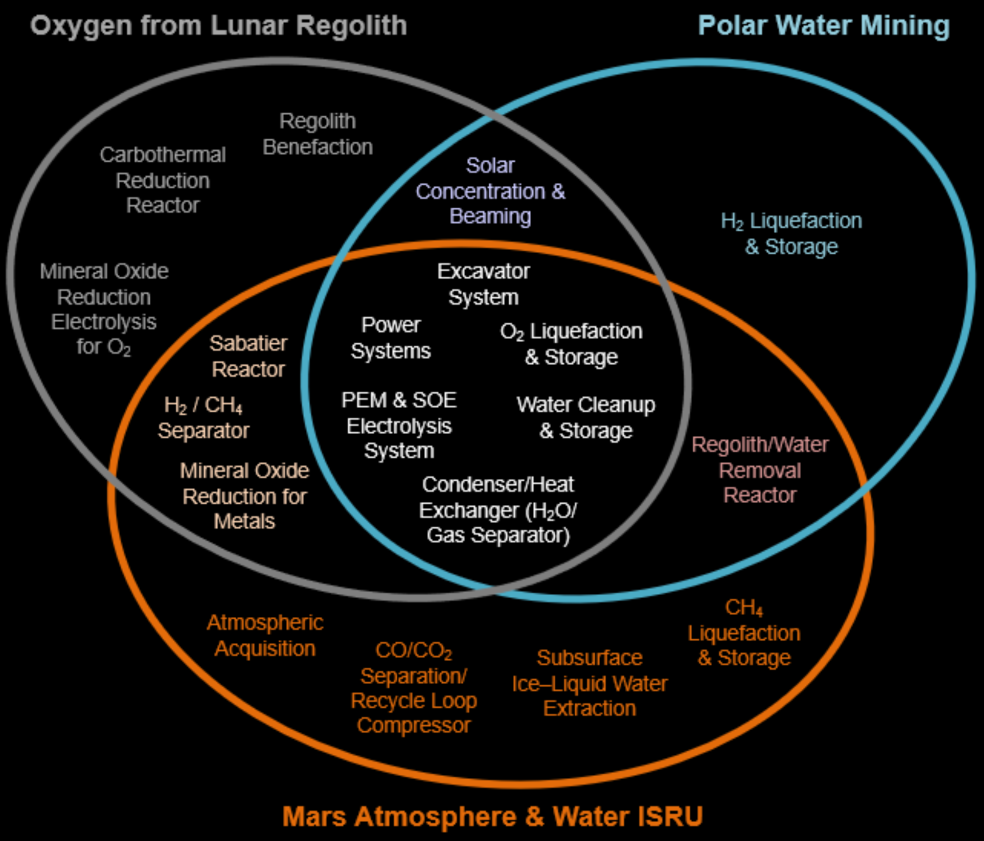
Moon to Mars Forward ISRU

- **Identify, characterize, and quantify environments and resources for Science and ISRU**
  - Quantify concentration and lateral/vertical distribution of resources/water/volatiles at multiple locations to provide geological context for science-focused theories of resource placement and initial mining assessments.
  - Test technologies and processes to reduce risk of future extraction/ mining systems

- **Demonstrate ISRU concepts, technologies, & hardware applicable to Mars**
  - ISRU for propellant production with modular/scalable hardware (both Moon and Mars require similar production rates)
    - Regolith excavation and delivery
    - Water and CO_2 collection, separation, chemical processing, and cleanup technologies
    - Liquefy, store, transfer, and fill ascent vehicle propellant tanks
  - Surface civil engineering and infrastructure emplacement for repeated landing/ascent at same location

- **Use Moon for operational experience and mission validation for Mars**
  - Pre-deployment & remote activation and operation of ISRU assets without crew; especially excavation
  - Making and transferring mission consumables (propellants, life support, power, etc.)
  - Landing crew with ‘empty’ tanks with ISRU propellants already made and waiting

ISRU Technology Synergy



Oxygen from Lunar Regolith

Polar Water Mining

Carbothermal Reduction Reactor

Regolith Benefaction

Solar Concentration & Beaming

H_2 Liquefaction & Storage

Mineral Oxide Reduction Electrolysis for O_2

Excavator System

Sabatier Reactor

Power Systems

O_2 Liquefaction & Storage

H_2 / CH_4 Separator

PEM & SOE Electrolysis System

Water Cleanup & Storage

Regolith/Water Removal Reactor

Mineral Oxide Reduction for Metals

Condenser/Heat Exchanger (H_2O/ Gas Separator)

Atmospheric Acquisition

CO/CO_2 Separation/ Recycle Loop Compressor

Subsurface Ice–Liquid Water Extraction

CH_4 Liquefaction & Storage

Mars Atmosphere & Water ISRU

Lunar & Mars Production Synergy

Lunar Production Target

10 mt O_2 / yr
or
15 mt H_2O / yr

Lunar ISRU

- Resource acquisition (225 – 1360 kg / day)
- Oxygen production (2.0 kg O_2 / hr)
- Water electrolysis (2.8 kg H_2O / hr)

Mars ISRU

- Resource acquisition (720 – 2660 kg / day)
- Oxygen production (2.2 – 2.7 kg O_2 / hr)
- Water electrolysis (3.0 kg H_2O / hr)

Mars Production Target

23 mt O_2 only
or
28 mt O_2 & 7 mt CH_4
per mission (~26 months)

Will use modularity to ensure applicability of hardware to both Moon and Mars ISRU

Emphasize Industry Involvement

Mining Economics and Mining Phases*

- Define Initial and Long-term Customer Needs and ISRU-derived Products
- Advance ISRU Technologies/Systems (thru solicitations, Public - Private Partnerships, Challenges)
- Focus NASA Work to Reduce Risk and Promote Investment (fundamental research, technology development, facilities, etc.)
  - Foster advancement of circular-economy and ‘responsible’ space mining practices
- Promote Industry-led development thru End-to-End Production of Commodities
  - Lower barriers of entry and help close the business case

Exploration Phase

- Reserve Definition
- Mining and Recovering Technology Readiness

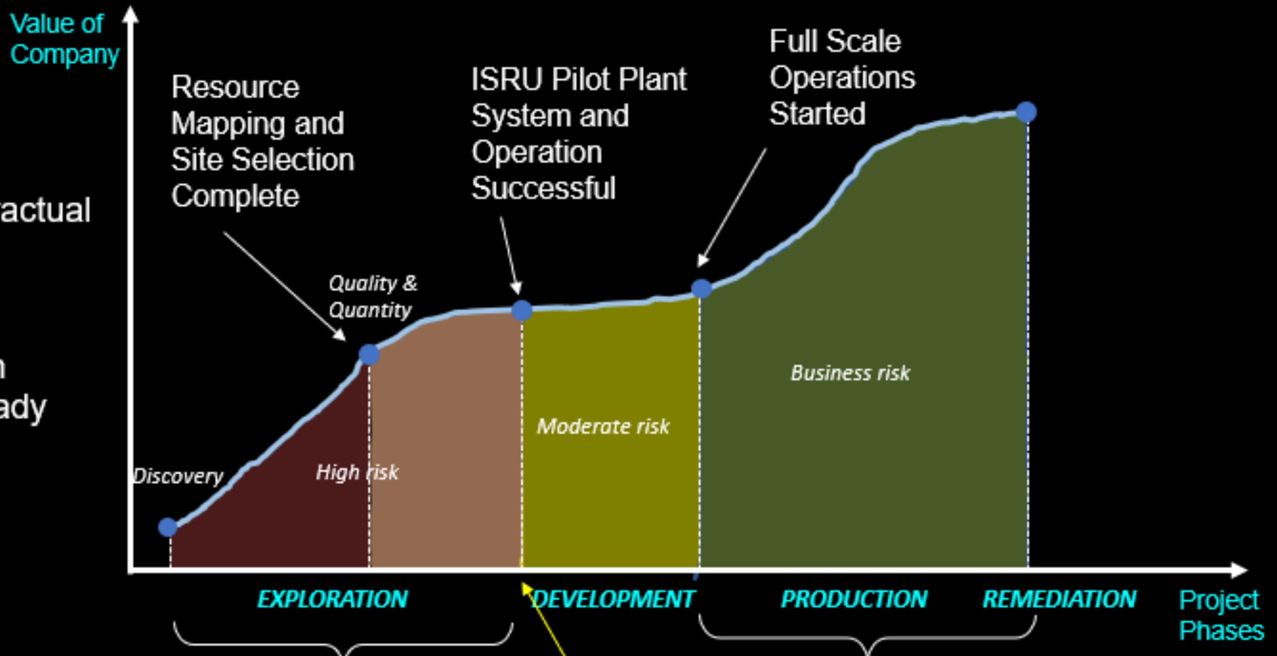
Development Phase: Feasibility study, contractual and legal aspects, and financing

Production

- Build-up Phase: Startup and initial production
- Plateau Phase: Production rate remains steady
- Decline Phase: Reserves begin to dwindle

Remediation

- Shutdown/removal of mining equipment
- Mine site reclamation



*Government support in **Exploration Phase** may be key to lunar commercial success*

Negative cash flow due to resource assessment and technology development and testing

Positive cash flow due to production and selling of product

Investment risk significantly reduced after successful Pilot Plant demonstration

*Sommariva, A. et al, “The Economics of Moon Mining’, International Academy of Astronautics, Torino, Italy, June 17-19, 2019

University & Public Involvement

ISRU Excavation, & Construction Related Challenges

Printed 3D Habitat Challenge
- Design, build habitat elements, and 3D print a subscale habitat
- Phase III completed 2019

Space Robotics Challenge
- Software for autonomous multi-agent ISRU activities: prospecting, excavating, and delivering
- Phase II completed 9/2021

CO_2 Conversion Challenge
- Convert CO_2 into sugars
- Phase I completed
- Phase II completed 8/2021

Watts on the Moon Challenge
- Solutions for energy distribution, management, and/or storage
- Phase I completed 5/2021

Break the Ice Challenge
- Excavate icy regolith in PSR
- Phase I completed 8/2021
- Phase II now open

Lunar PSR Challenge 2020
– 8 university teams; mobility, power beaming, tether, and wireless charging, instrument, and tower
  - Winner: MTU superconducting cable deployment

Lunar Dust Challenge 2021
- Landing Dust Prevention and Mitigation
- Spacesuit Dust Tolerance and Mitigation
- External Dust Prevention, Tolerance and Mitigation
- Cabin Dust Tolerance and Mitigation

Lunar Forge Challenge 2023
- Producing Metal Products on the Moon

Lunar Surface Technology Research (LuSTR)
- 2020. Advanced techniques for extracting and processing of water from lunar soil, or regolith; Methods for determining the distribution and properties of water-bearing regolith
  - 3 teams selected
- 2021. Construction and Regolith beneficiation
  - 2 teams selected

Moon Mars Ice Challenge
- Yearly, university, started in 2017 for Mars ice; added Moon in 2019
- Understand subsurface stratigraphy/hardness
- Extract subsurface water
- 10 teams compete in final 2 day event at LaRC

Lunabotics Robotic Mining Competition
- Started in 2007 following Lunar Excavation Centennial challenge
- Design/build robotic machines to excavate simulated lunar soil
- Teams compete at KSC

Over the Dusty Moon 2022
- Convey regolith 3 m high x 5 m

ISRU EFP - Next Step Priorities

- **~~Initiate solicitations with Industry to progress ISRU technologies to Demonstration & Pilot-scale flights~~**
  - Pursue oxygen and metal extraction demonstrations; delay water mining demonstration until better knowledge is obtained
  - Provide feedstock technologies and capabilities to support construction demonstrations
  - Identify and pursue new options/approaches for utilizing significant mission mass/frequency capabilities with HLS providers
- **Initiate Internal and Industry-led System-level integration of ISRU and infrastructure capabilities for Pilot/Full-Scale**
  - Expand ISRU system engineering, modeling, integration, and testing to enable technology and system selections
  - Begin combining power, excavation, ISRU, storage & transfer, comm/nav, autonomy/avionics, maintenance/crew.
- **Expand Development of Metal/Aluminum Extraction & other Feedstock for Manufacturing & Construction**
  - Continue and expand work on combined oxygen and metal extraction technologies;
  - Initiate work focused on metal extraction and processes leading to more pure/refined metals
  - Consider longer-term interests in mare regolith minerals and resources: Ilmenite, Pyroclastic glasses, KREEP, Solar wind implanted volatiles
  - Continue and expand construction feedstock/commodity development with in-space manufacturing and construction
  - Evaluate synthetic biology technologies for bio-mining, bio-plastic, and some commodity feedstocks
- **Initiate Mars ISRU Technology and System Risk Reduction Development and Testing for M2M Objective MI-4**
  - Perform system Integration of existing/near-existing Mars human mission scale hardware and perform testing to reduce the risk for architecture insertion
  - Coordinate evaluation of Mars resources and mission insertion with SMD and ESDMD/SOMD
- **Advance Lunar Polar Water/Volatile Prospecting/Mapping and Technology Development**
  - Coordinate Polar Resource Assessment and Mapping (M2M AS-3) with SMD, ESDMD/SOMD, and industry for mining site selection
  - Continue evaluating/developing water mining technologies in parallel with polar resource assessment
- **Initiate Closer-Ties and Coordination with Life Support Systems**
  - Develop needs/objectives, and perform technology assessment/development for nutrients/food/agriculture feedstocks for sustained presence
  - Work with life support on oxygen and water cleanup technologies and requirements
  - Work with life support on conversion of wastes into usable products; eliminate trash dumping

Thank You. Questions?

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

BACKUP

Space Resource Utilization Is Synergistic with Terrestrial Needs

Food/Water

- *Improve water cleanup techniques*
- *Advance food/plant growth techniques and nutrient production*

Construction

- *Reduce or eliminate cement and asphalt – renewable materials*
- *Alternative construction techniques – 3-D printing, no Portland cement*
- *Remote operation and automation*

Mining

- *Increase safety*
- *Reduce maintenance and logistics*
- *Increase mining and processing efficiency*
- *Improve environmental compatibility*

Energy

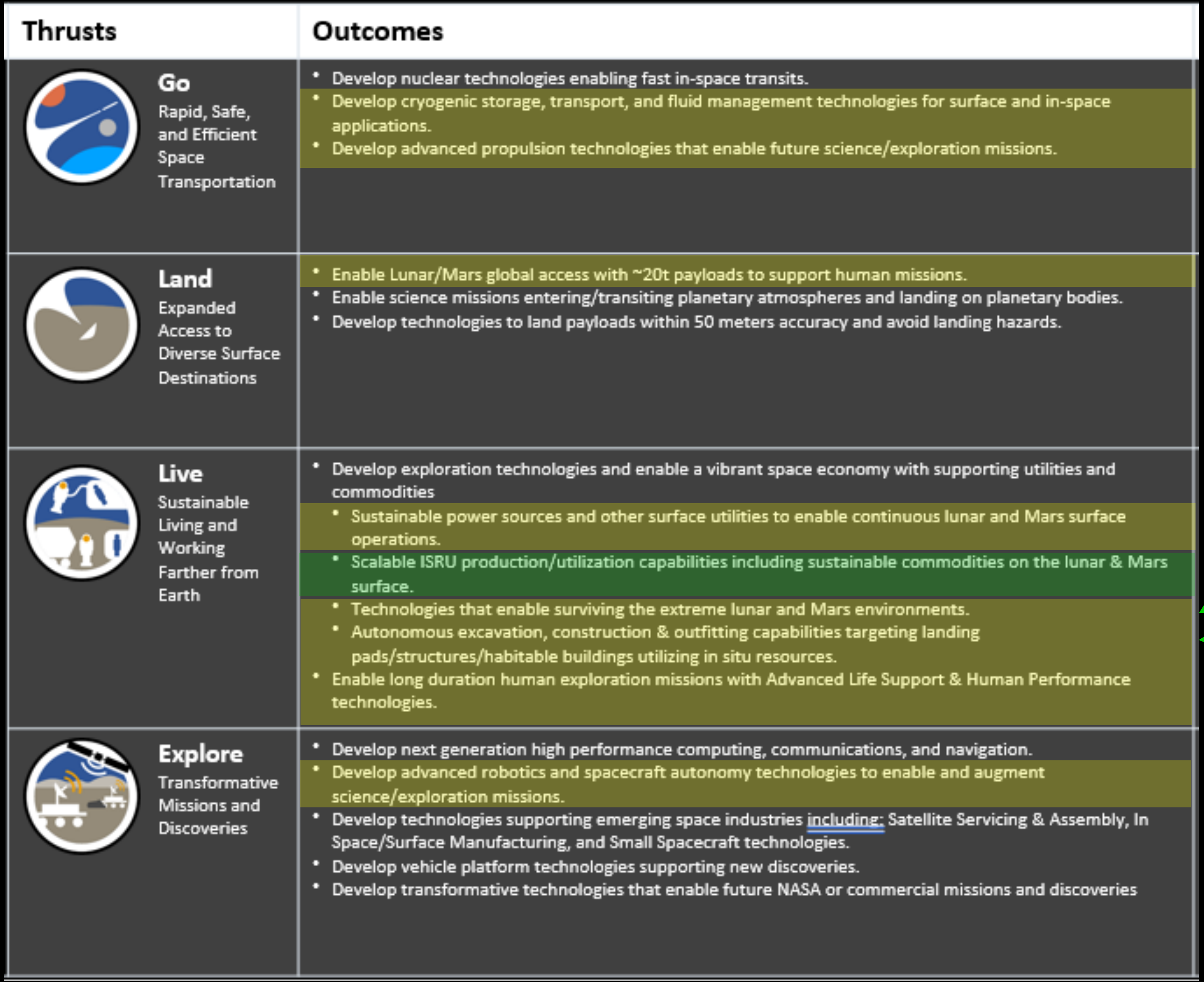
- *More efficient power generation, storage and distribution*
- *Increase renewable energy: Use sun, thermal, trash, and alternative fuel production*
- *Reduction of Carbon Dioxide emissions*

Promote *Reduction, Reuse, Recycle, Repair, Reclamation*

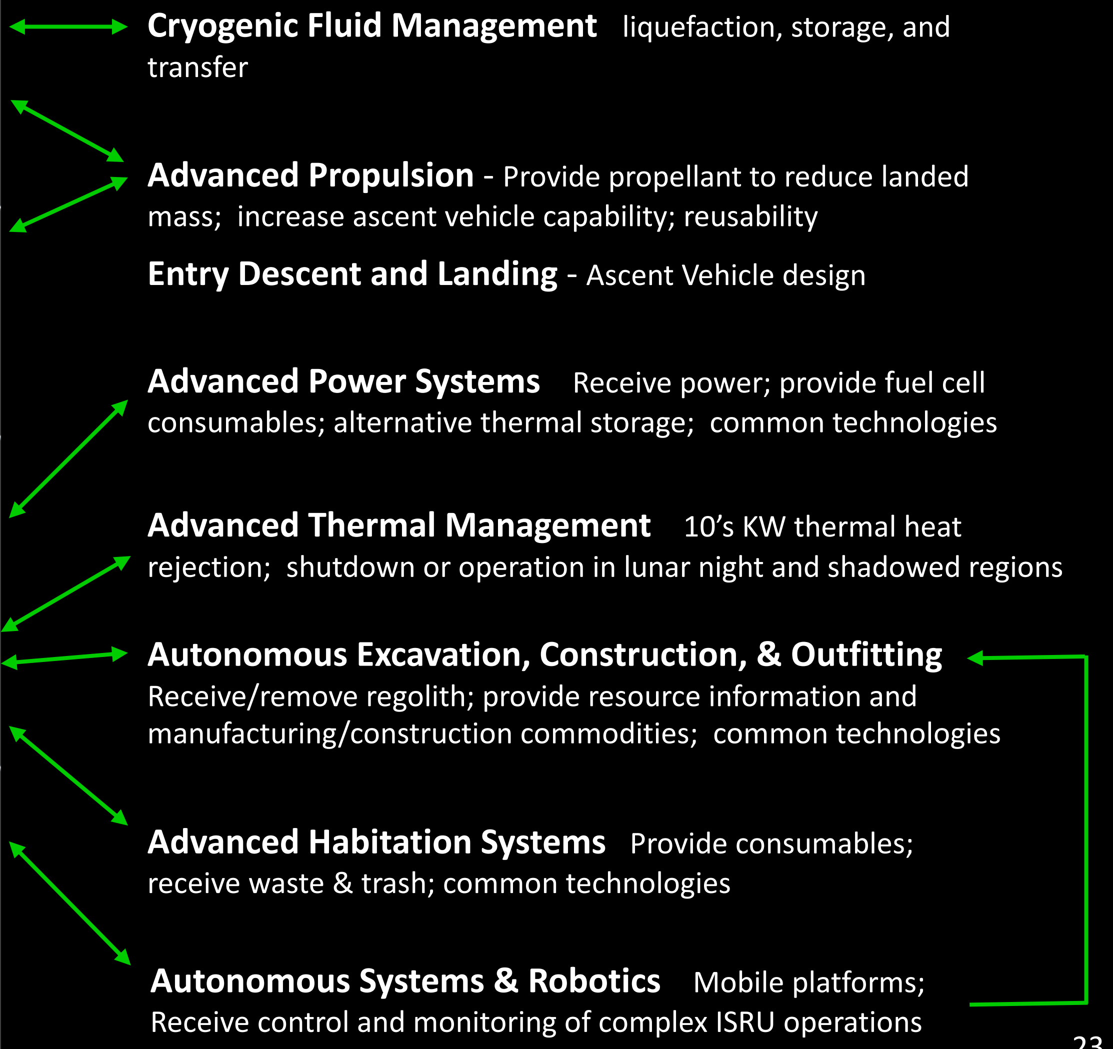
…for benefit of Earth, and living in Space.

IN SITU RESOURCE UTILIZATION (ISRU) INTERFACES WITH MULTIPLE STRATEGIC OUTCOMES AND REQUIRE SUPPORT FROM OTHER PT/SCLTS

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



Thrusts	Outcomes
Go Rapid, Safe, and Efficient Space Transportation	• Develop nuclear technologies enabling fast in-space transits. • Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications. • Develop advanced propulsion technologies that enable future science/exploration missions.
Land Expanded Access to Diverse Surface Destinations	• Enable Lunar/Mars global access with ~20t payloads to support human missions. • Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies. • Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards.
Live Sustainable Living and Working Farther from Earth	• Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations. • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface. • Technologies that enable surviving the extreme lunar and Mars environments. • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources. • Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies.
Explore Transformative Missions and Discoveries	• Develop next generation high performance computing, communications, and navigation. • Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions. • Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies. • Develop vehicle platform technologies supporting new discoveries. • Develop transformative technologies that enable future NASA or commercial missions and discoveries



Cryogenic Fluid Management liquefaction, storage, and transfer

Advanced Propulsion - Provide propellant to reduce landed mass; increase ascent vehicle capability; reusability

Entry Descent and Landing - Ascent Vehicle design

Advanced Power Systems Receive power; provide fuel cell consumables; alternative thermal storage; common technologies

Advanced Thermal Management 10's KW thermal heat rejection; shutdown or operation in lunar night and shadowed regions

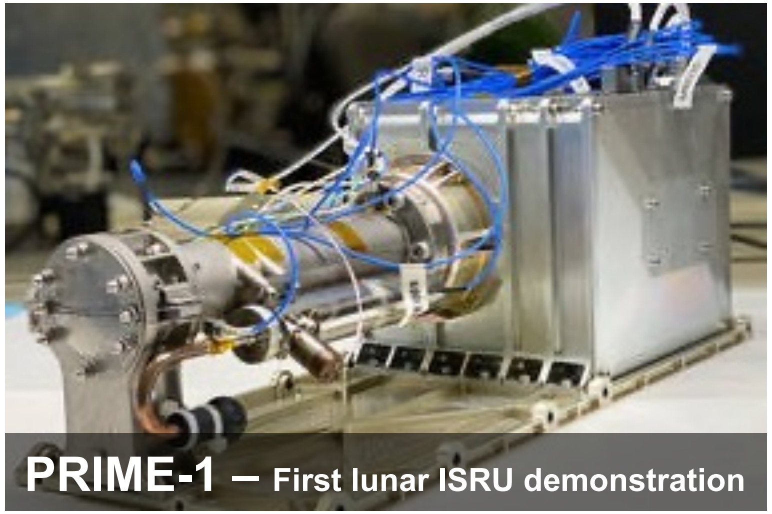
Autonomous Excavation, Construction, & Outfitting Receive/remove regolith; provide resource information and manufacturing/construction commodities; common technologies

Advanced Habitation Systems Provide consumables; receive waste & trash; common technologies

Autonomous Systems & Robotics Mobile platforms; Receive control and monitoring of complex ISRU operations

In-Situ Resource Utilization Instruments and Vehicles

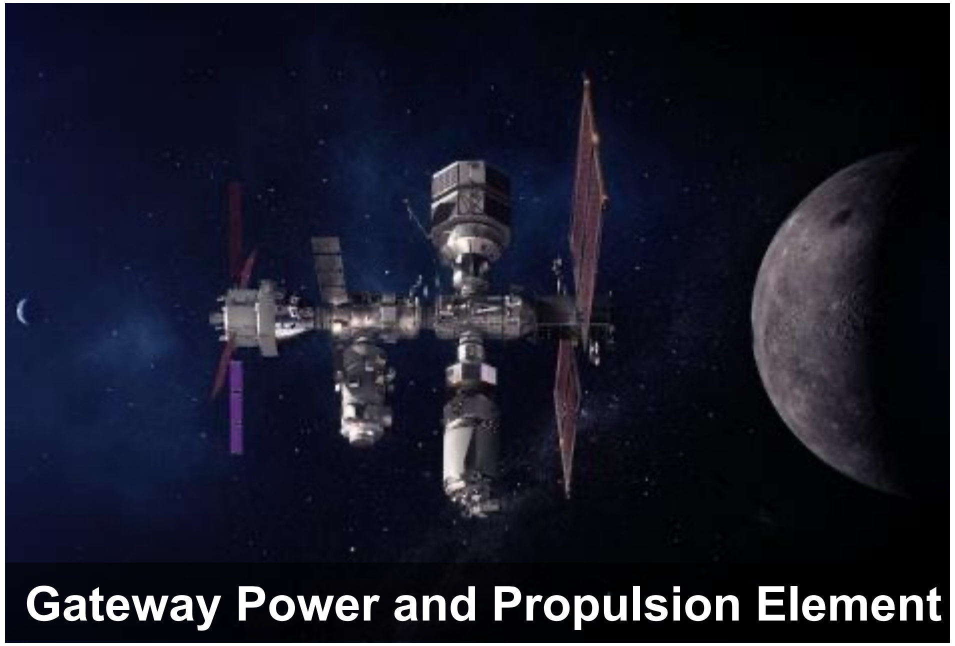
MOXIE – Oxygen from Mars Atmosphere



PRIME-1 – First lunar ISRU demonstration

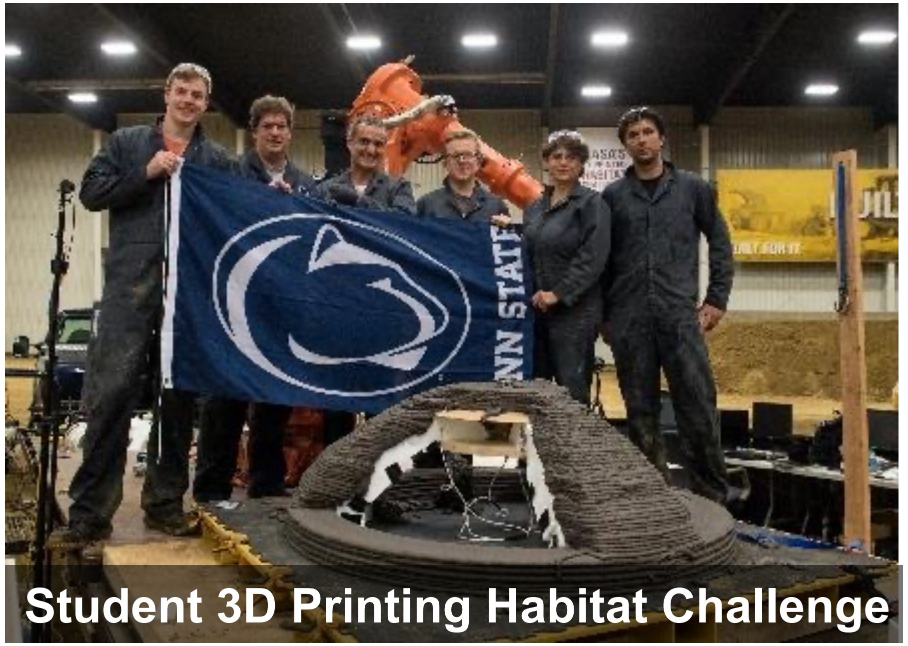
VIPER – Origin and distribution of lunar resources

ISRU Pilot Excavator – Digging up to 10 mT of lunar regolith



Gateway Power and Propulsion Element

Artemis ISRU Demo Plant



Student 3D Printing Habitat Challenge

Technology Drives Exploration