EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

In Situ Resource Utilization (ISRU)

Presentation to Decadal Survey on Biological and Physical Sciences Research in Space 2023-2032 Meeting #7

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Presentation Topics

- **Lunar ISRU In the Next Decade: Development & Insertion Strategy**

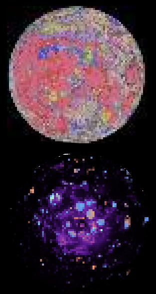
- **ISRU-relevant Biological and Physical Sciences Research**

Lunar ISRU In the Next Decade:
Development & Insertion Strategy

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

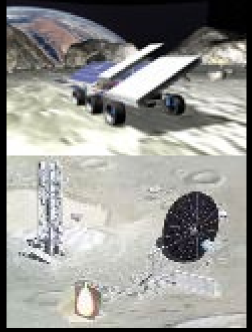


- Lunar resources mapped at meter scale for commercial mining
- Initial 10's of metric tons of commodities per year
- Scalable to 100's to 1000's metric tons of commodities per year

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

- Initially 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

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

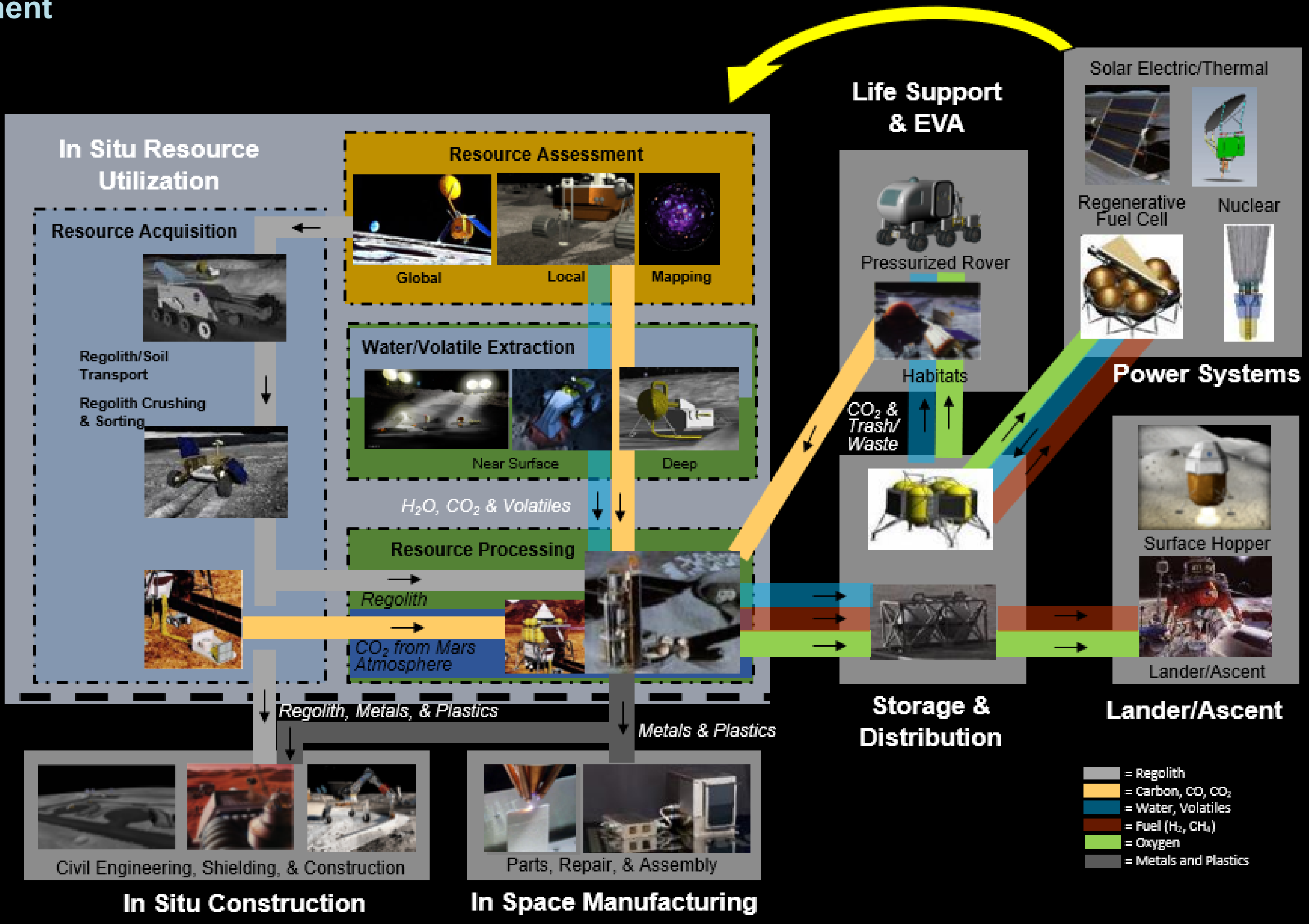
Resource Processing

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

Lunar ISRU Commodities:
Polar Water, Oxygen from Regolith, and Feedstock

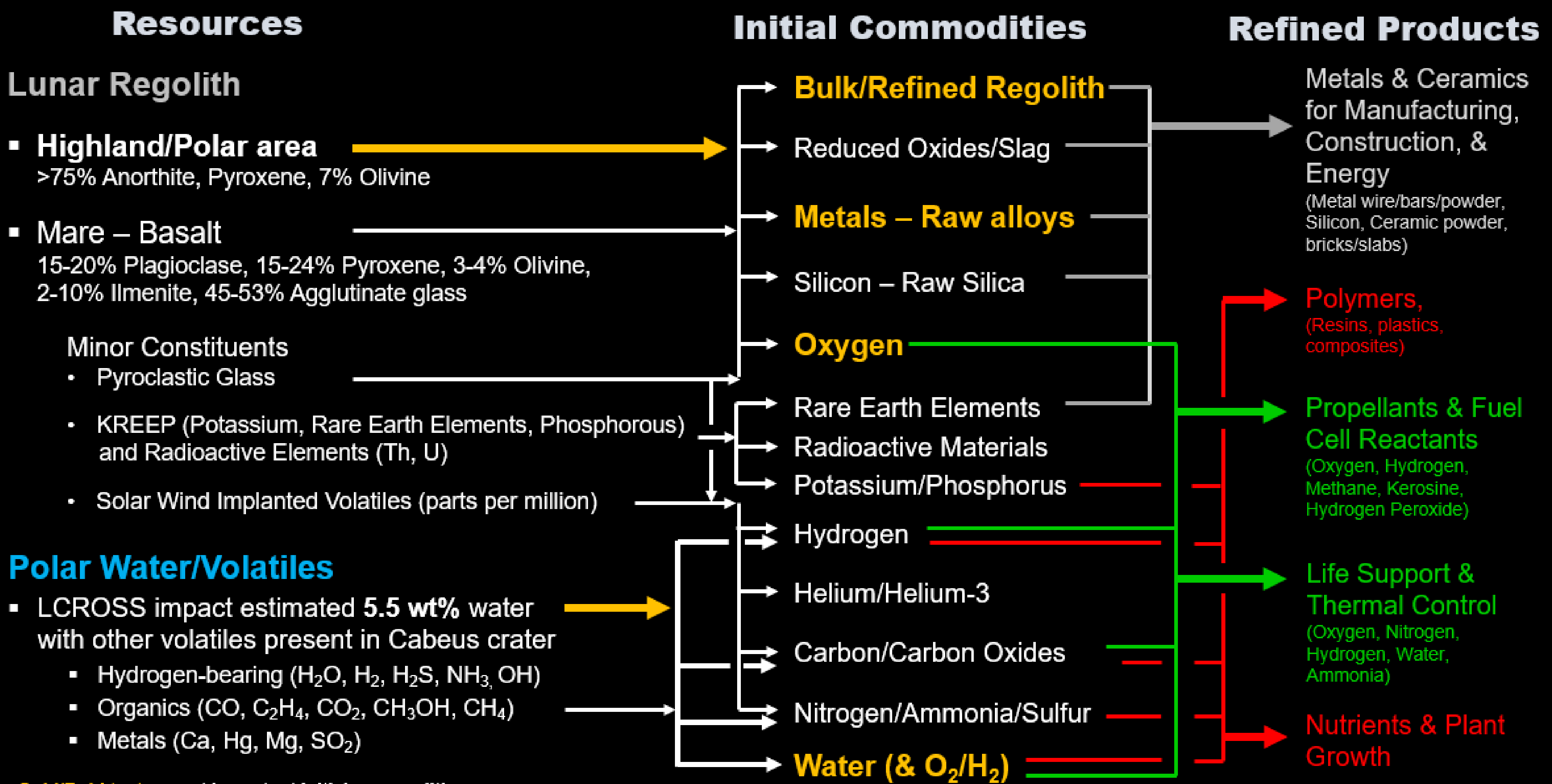
- **Water (and Volatiles) from Polar Regolith**
  - Form, concentration, and distribution of Water in shadowed regions/craters is not known
    - Technologies & missions in work to locate and characterize resources to reduce risk for mission incorporation
  - Provides 100% of chemical propulsion propellant mass
  - 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
  - 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

- **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

Lunar Resources and Commodities

- 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



Gold/Bold text = most important initial commodities

Plan to Achieve ISRU Outcome

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

- **Know Customer Needs (Type and Quantity of Commodities) & Develop Suppliers**
  - Work with Artemis elements, Moon/Mars Surface Architecture, and International Partners
  - Work with Commodity users: Life Support & Food Production, Propulsion, Manufacturing, Construction
  - Understand all processing system wastes (life support, ISRU, manufacturing, construction) as potential new resource
  - ➢ Work with Terrestrial/Space Industry & Lunar Surface Innovation Consortium for Commercial Involvement & Opportunities

- **Perform Ground Development of Hardware and Systems until Ready for Lunar Flight**
  - Initiate a full range of ISRU & other discipline technologies across all TRLs (Technology Pipeline) to enable ISRU capabilities
  - Perform gravity related research (short duration & ISS) on material handling, resource processing, and feedstock behavior
  - Integrate lunar ISRU technologies and subsystems into systems for environmental and operational testing
  - Develop lunar ISRU components, subsystems, and operations (including autonomy) applicable to Mars ISRU systems
  - ➢ **Engage Industry, Academia, and the Public** to lay the foundation for long-term lunar economic development

- **Reduce Risk of ISRU for Human Exploration & Space Commercialization thru CLPS Missions**
  - Understand lunar polar resources for technology development, site selection, mission planning
  - Obtain critical data (ex. regolith properties, validate feasibility of ISRU processes)
  - Demonstrate critical ISRU technologies in lunar environment, especially those that interact with and process regolith

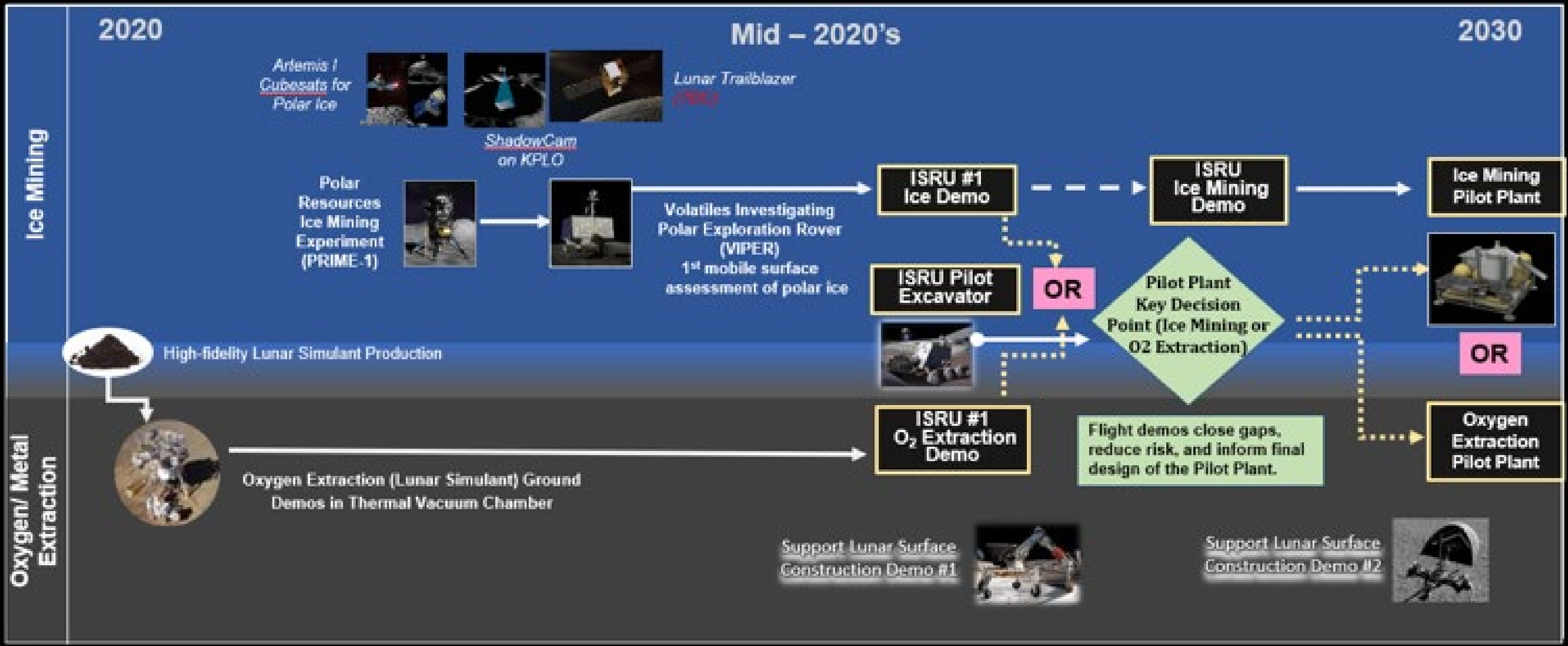
- **Perform End-to-End ISRU Production of Commodities & Demonstrate Usage**
  - Production at sufficient scale to eliminate risk of Full-scale system
  - Initially use ISRU-derived commodity in non-mission critical application; examples include non-crewed ascent vehicle or hopper, extra fuel cell power, extra crew and EVA oxygen, construction demonstration, etc.
  - ➢ **Involve industry in ISRU Demos and Pilot Plant to transition to Full-scale commercial operations**

➢ **ISRU must be demonstrated on the Moon before mission-critical applications are possible**

- NASA STMD is breaking the 'Chicken & Egg' cycle of past ISRU development priority and architecture insertion issues by developing and flying ISRU demonstrations and capabilities to the Pilot Plant phase

ISRU Path to Full Implementation & Commercialization*

**Proposed missions are contingent on appropriations and technology advancement*



Reconnaissance, Prospecting, Sampling	Resource Acquisition & Processing	Pilot Consumable Production
Sub-system Demonstrations: Investigate, sample, and analyze the environment for mining and utilization.	*Demonstrations for extraction and processing of raw materials for mission consumables production and storage.*	*Sustainable Exploration: Scalable Pilot Systems producing consumables from in-situ resources in order to support sustained human presence.*

Full-scale implementation & Commercial Operations

- Dual Path that includes both Water Mining and Oxygen/Metal from Regolith
  - O_2/Metal Path supports Surface Construction 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
  - PRIME-1 validates critical VIPER instruments and lunar highland material properties (for subsequent ground development)
- Demonstrations are aimed at reducing the risk of Pilot Plant design and operation (and subsequent Full-scale implementation)
  - Pilot Plant demonstrates performance, end-to-end operations, and quality of product for implementation and use

ISRU Commodity Production Investment Status (1 of 2)

- **Develop Critical Technologies for Lunar Oxygen Extraction**
  - ☑ Close coordination with Autonomous Excavation, Construction, and Outfitting (AECO) on excavation and delivery
  - ☑ 6 different O_2 extraction technologies in development
  - ☑ 9 development projects for 3 different water electrolysis approaches (with Life Support and Regenerative Power)
  - ❑ Interface and internal technologies/functional areas require further investment

- **Develop Critical Technologies for Lunar Resource Assessment and Water Extraction**
  - ☑ Significant number of SMD and STMD instrument technologies for resource assessment down to 1 m.; University/Public Challenges
  - ☒ Need to consider technologies for deeper >3 m assessment for water/volatiles based on some water deposit theories
  - ☑ Close coordination with AECO on excavation in Permanently Shadowed Regions (PSRs); Break the Ice Lunar Challenge
  - ❑ 6 water mining development projects for 3 different approaches
  - ☑ 9 development projects for 3 different water electrolysis approaches (with Life Support and Regenerative Power)
  - ❑ Interface and internal technologies/functional areas require further investment
  - ☒ No dedicated robotic polar water/volatile resource assessment surface missions beyond VIPER currently in planning
  - ☒ No dedicated funded effort to develop resource maps for site selection

- **Develop Critical Technologies for Manufacturing and Construction Feedstocks/Commodities**
  - ❑ Technologies for raw metal/alloy extraction in work as part of O_2 extraction; work required to further separate and refine metals
  - ❑ Technologies for regolith size sorting, mineral beneficiation, and regolith manipulation in work
  - ❑ Development and evaluation feedstocks to support manufacturing and construction techniques
  - ☒ Limited plastic/binder production from in situ resources; synthetic biology technologies in work for bio-plastic and some commodity feedsocks

- **Evaluate and Develop Integrated Systems for Extended Ground Testing; Tie to Other Discipline Plans**
  - ☑ NASA and APL performed/performing ISRU system evaluations
  - ❑ Dedicated modeling, evaluation criteria, and Figures of Merit (FOMs) established
  - ❑ Approach/approval for NASA and/or Industry-led System development and testing
  - ☑ Facilities and simulants to support lunar environmental testing with regolith simulants
  - ❑ Facilities and approach for extended mission analog operation and evaluation ground testing

Green = Significant Funded Activities
Yellow = Partially Covered; More Required
Red = Limited/No Funded Activities

ISRU Commodity Production Investment Status (2 of 2)

- **Develop/Fly Resource Assessment & ISRU Demonstrations Missions leading to Pilot Plant operations by 2030**
  - ☑ Orbital missions, PRIME-1, & VIPER funded and under development for launch
  - ❑ Lunar Trailblazer launch date and mission data later than desired. Actual spacecraft ready for launch in 2022
  - ☒ No clear plan for polar water/volatile resource assessment leading to Base Camp site selection – predicated on success of VIPER
  - ❑ At least one demonstration planned for each ISRU commodity path
- **Involve Industry/Academia with Goal of Commercial Space Operations at Scale**
  - ☑ 25 NIACs, SBIRs, BAAs, ACOs, & TPs led by industry underway for ISRU
  - ☑ 9 STTRs, NIACs, LuSTR, NSTRF, ESI/ECF led by Academia underway for ISRU
  - ☑ Lunar Surface Innovation Consortium – ISRU Focus Group underway and active; Supply/Demand Workshop
  - ☑ Center for the Utilization of Biological Engineering in Space (CUBES)
  - ☑ NASA prize competitions and university challenges: BIG Idea, Moon-Mars Ice Prospecting, Break the Ice Lunar, Lunabotics, CO_2 Conversion Challenge, Space Robotics Challenge
  - ❑ Selection/Competition strategy for ISRU demonstrations and Pilot Plant in work for industry involvement and commercialization

Green = Significant Funded Activities
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Red = Limited/No Funded Activities

ISRU Commodity Production Summary and Next Step Priorities

- **Complete Development of Water/Oxygen Mining Paths and Close Technology Gaps**
  - Continue oxygen extraction of Highland regolith
  - Continue water extraction/mining approaches in parallel until mission data allows for down-selection
    - Work with life support on oxygen and water cleanup technologies and requirements

- **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 wider range of regolith options: Mare regolith, Pyroclastic Glasses, and KREEP
  - 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

- **Coordinate Polar Resource Assessment with SMD and ESD/SOMD for Artemis Base Camp site selection**

- **Initiate Internal and Industry-led System-level integration of ISRU and infrastructure capabilities**
  - 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.

- **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

ISRU-relevant Biological and Biological and Physical Sciences Research

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

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

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?

Scale up, Long-duration, & Environmental testing with Realistic simulants Required

ISRU Capability Gaps to Achieve Initial Full-Scale Production*

*Estimates from Internal NASA and APL Lunar Surface Innovation Consortium Supply/Demand Workshop 9/17/2020)

Resource Assessment (Lunar Water/Ice) Capability Gaps
- Surface features and geotechnical data on regolith outside and inside permanently shadowed craters (PSRs)
- Understanding of water and contaminants as a function of depth and areal distribution
- Understanding of subsurface water/volatile release with heating
- Resolution of hydrogen and subsurface ice at <10s m scale (or less) for economic assessment & mine planning (orbital/surface)
- Instrument for polar regolith sample heating and released volatile characterization (minimum loss during transfer/evaluation)

Water Mining Capability Gaps
- Feasibility and operation of downhole ice/water vaporization and collection in cold-trap under lunar PSR conditions
- Feasibility and operation icy regolith transfer (low loss) and processing in reactor under lunar PSR conditions; min. 15,000 kg/yr; 3 years nom.
- Water and other volatile capture and separation; contaminant removal
- Electrical power & Thermal energy in PSRs for ice mining/processing (10s of KWs) – *Power System Gap*

Oxygen Extraction Capability Gaps
- Industrial-scale of regolith processing for oxygen (minimum of 10 mT O_2/yr; 3 years nom. with min./no maintenance)
- Regenerative oxygen & product gas clean-up (10,000 kg/yr)
- Measuring mineral properties/oxygen content before and after processing

Manufacturing & Construction Feedstock Capability Gaps
- Metal and metal alloy extraction from regolith: Post oxygen extraction or separate/multi-step refining
- Crushing, size sorting and mineral beneficiation of 100s mT per project for extraction and manufacturing/construction feedstock
- Production of 10s mT per project of plastic/binders and cement for manufacturing and construction

Regolith Excavation, Handing, & Manipulation Capability Gaps
- Long-life, regolith transfer (100s of mT) and low leakage regolith inlet/outlet valves for processing reactors (10s of thousands of cycles)
- Excavation and delivery of granular regolith (O_2/Metal) and icy regolith (Water Mining) – *Autonomous Excavation, Construction, & Outfitting (AECO)*
- Extensive Traversibility (100s of km in sunlit and PSR locations and ingress/egress – *Autonomous & Robotic Systems Gap*

Cross-Cutting/System Level Resource Gaps
- Gravity-related research (short duration & ISS) to better understand impact on material handling, resource processing, and feedstock behavior
- Long-duration (100s of days) and Industrial-scale (10s of mT) operations under lunar vacuum and at <100 K temperatures
- Sensors and autonomous process monitoring and operations
- Industrial-scale water electrolysis water electrolysis, clean-up, and quality measurement for electrolysis or drinking (10s of mT/yr)

ISECG ISRU Gap Assessment*

Strategic Knowledge Gaps (SKGs) – Resource Assessment & Operations

- Reviewed 2016 LEAG Strategic Knowledge Gap (SKG) Special Action Team (SAT) Review
- Focused on Two of the Three Themes
  - Theme 1 – Understand the Lunar Resource Potential
  - Theme 3 – Understand How to Work and Live on the Lunar Surface

Each SKG assessed for the 5 major ISRU Functions and Products

Each SKG defined at one or more sub-element for ISRU

Each SKG Linked to one or more Architecture Phase and Objective

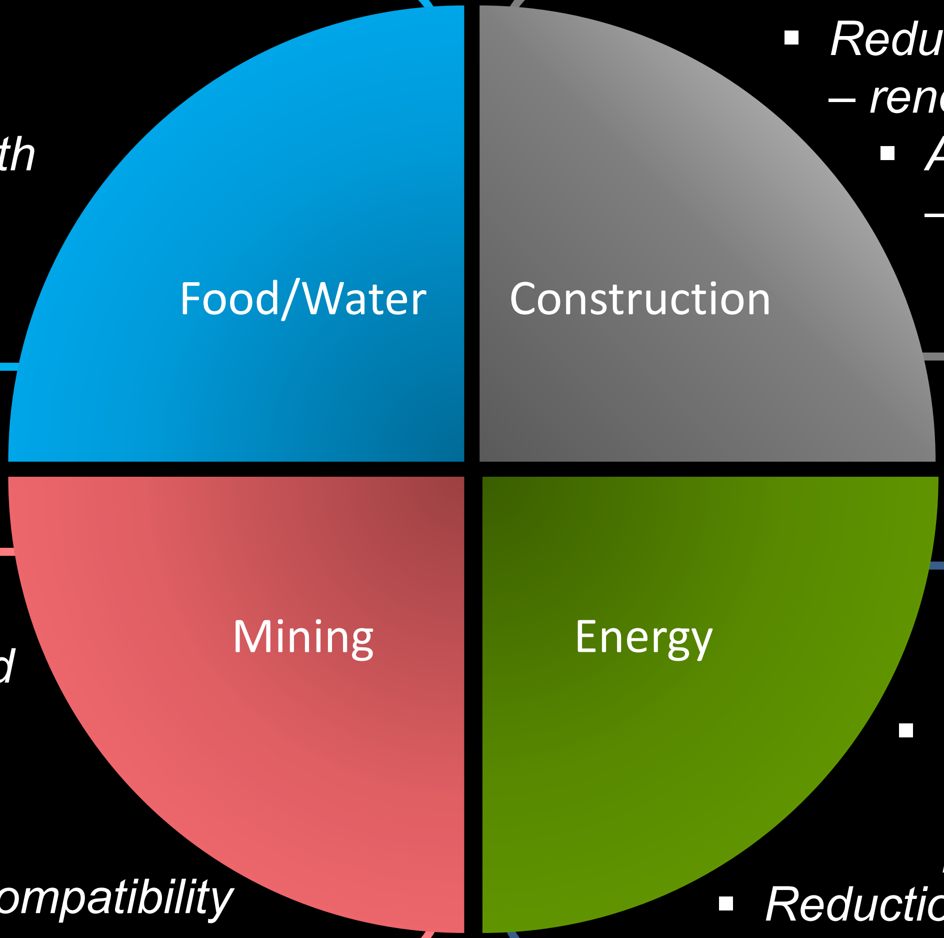
Polar Water (& polar volatiles)	Solar Wind Volatiles	O_2 from Regolith	Construction & Manufacturing	ISRU Ops	LEAG Designation	Strategic Knowledge Gap Title	Strategic Knowledge Gap Subelements	Categorization & Min. Gap Closure Approach	Architecture Integration
						I. Understanding the Lunar Resource Potential	**Breakdown/Narative**	**Science/Technology; Ground/Flight**	
						B. Regolith (Earth Testing)			
	L	M			1	Quality/quantity/distribution/form of H species and other volatiles in mare and highlands regolith. Apollo heritage (samples)	Measure volatiles and organics returned in "pristine" Apollo samples. Measure the extent of disruption of volatiles during handling and processing	Science/Ground	
	L	M					Measure volatiles and organics returned from new locations on the lunar surface, and measure the extent of disruption of volatiles during handling and processing. Utilize new technologies to minimize sample container leakage and oxidation of samples returned	Science/Ground	
						C. Regolith (Moon Volatiles- non PSR)	Multiple measurements of undisturbed soil at depth at meter and decameter scales (laterally) and 0 2m depth. Need to measure abundance of solar wind gases or H species at the 10 ppm level. Need capability for multiple analyses at different locales and subsurface depths		
	M				2	Quality/quantity/distribution/form of H species and other volatiles in mare and highlands regolith	Knowledge of hydrogen-resources in Mare and HighIand regolith at non-polar locations: location, type, concentration in different minerals, energy to release	Science/Flight	S1.1, 1.2, 1.3, 1.4, 1.5, 1.8
	H						Knowledge of hydrogen-resources in non-PSR regolith at polar locations: location, type, concentration in different minerals, energy to release tied to physical/mineral characterization	Science/Flight	S1.1, S1.2, S1.3, S1.5, S1.8
	M						Measure volatiles and organics released from returned samples	Science/Flight & Ground	
	M						Losses of volatiles (solar wind deposited) in regolith during excavation and processing	Technology/Flt Demo	S1.2, S1.5

H = High Impact - Important for initial sustained operation at the lunar polar region (according to Artemis program)
M = Medium Impact - Important for longer-term sustained operations or for non-polar regions
L = Low Impact - Limited importance to area of ISRU; limited impact to the architecture

ISRU Operations
- Definition: The SKG is applicable to all ISRU areas as well as potentially other surface activities., e.g. communication and navigation
- Impact is assessed for each ISRU area. A single impact designation in the ISRU Ops column means all other colored columns have the same priority

*Final report https://www.globalspaceexploration.org/wordpress/wp-content/uploads/2021/04/ISECG-ISRU-Technology-Gap-Assessment-Report-Apr-2021.pdf

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.

ISRU Operation Challenges – Further Details (1 of 2)

- **Operation in low/micro-gravity**
  - Low-gravity on Moon/Mars
    - Solids
      - Low reaction force excavation in reduced and micro-gravity
      - Granular material flows differently in low-g; increase in electrostatic/friction effects
      - Kicking up dust is amplified; dust settling is different
      - Rotational inertia is not reduced, but gravity to resist tipping is reduced!
      - Fluidized gas/solid reactors impacted by gravity and thermal convection differences
    - Liquids
      - Liquid slosh is amplified
      - Influence of surface tension
      - Liquid & molten reactors impacted by gravity and thermal convection differences
      - Unknown impact on biological processing
  - Micro-g environment for Near Earth Asteroids (NEAs) and Phobos/Deimos
    - Solids
      - Anchoring/weight-on-bit for resource extraction
      - Material handling and transport completely different than Moon/Mars techniques
      - Feedstock, product, and reactant separation: Gas/solid reactors and separation
      - Friction, cohesion, and electrostatic forces may dominate in micro-g
    - Liquids
      - Influence of surface tension
      - Unknown impact on biological processing
      - Feedstock, product, and reactant separation: Gas/liquid and liquid/solid reactors and separation

- **ISRU Operations**
  - Granular flow for excavation and transfer
  - Granular size sorting
  - Granular mineral separation: electrostatic, tribocharing, magnetic fluid, etc.
  - Granular material processing (gas/solid)
  - Liquid/granular processing: solid/liquid, and molten regolith
  - Gas/liquid and liquid/liquid processing for reactant regeneration and biological processing

ISRU Operation Challenges – Further Details

- **Operation in severe environments**
  - Efficient excavation of resources in dusty/abrasive environments; Wide variation in potential resource hardness, density/porosity, etc.
  - Methods to mitigate dust & dust filtration for Mars atmospheric processing
  - Extreme temperature changes (PSR ingress/egress) and/or extremely low temperatures (PSRs)
    - Material selection, embrittlement, thermal management, etc.
  - Radiation
    - Regolith charge: grounding/electrostatics
    - Impact on biological systems
  - Vacuum operation and exposure: electronics/power systems, reactor pressures/leakage, cold welding, etc.

- **ISRU Operations**
  - Granular flow for excavation and transfer
  - Granular size sorting
  - Granular mineral separation: electrostatic, tribocharing, magnetic fluid, etc.
  - Granular material processing (gas/solid)
  - Liquid/granular processing: solid/liquid, and molten regolith
  - Gas/liquid and liquid/liquid processing for reactant regeneration and biological processing

ISRU Development Plan Takeaways

- **ISRU has a number challenges and knowledge gaps to overcome to be successful**
  - Understanding Resources, Environments, and Environmental Impacts on hardware and processes is Critical
- **Technologies are being developed for both Oxygen/Metal Extraction and Polar Ice Mining**
  - Due to uncertainty in form, concentration, and distribution of polar water/volatiles, multiple options are being pursued in parallel until further resource information is available for down selection
  - The Mining Water path schedule is dependent on VIPER mission success
  - Technologies and demonstrations are aimed at supporting scale up for commercial operations.
- **Flight Demonstrations planned that will lead to Pilot plant scale operations before 2030**
- **Biological and Physical Sciences Research Can be extremely beneficial for ISRU**
  - Increased understanding of micro & low-g environment and influences on ISRU material flow, separation, and processing: especially for granular solids and liquids
  - Increased knowledge on reaction kinetics
  - Increased understanding of radiation and micro & low-g environment and influences on biological processing of solids and production of plastics/nutrients

Thank you.

Questions?

www.nasa.gov/spacetech

Backup

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 – completed Jan. 2021
- – 8 university teams; mobility, power beaming, tether, and wireless charging, instrument, and tower
- – Winner: MTU superconducting cable deployment

Lunar Dust Challenge 2021 – launched Sept. 2020
- Landing Dust Prevention and Mitigation
- Spacesuit Dust Tolerance and Mitigation
- External Dust Prevention, Tolerance and Mitigation
- Cabin Dust Tolerance and Mitigation

Update

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. Regolith beneficiation.

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
- Yearly, university, started in 2007 following Lunar Excavation Centennial challenge
- Design and build robotic machines to excavate simulated lunar soil (in 30 min.)
- Teams compete at KSC

ISRU Incremental Growth
Phases of Evolution and Use

Demonstrate, Build Confidence, Increase Production and Usage

10 to 30 mT Range for Initial Full Scale Production

	Demo Scale	Pilot Plant	Crewed Ascent Vehicle[1]	Full Descent Stage[1]	Lockheed Martin[6]		Dynetics[6] Single Stage/ Drop Tanks	Single Stage to NRHO[2]	Human Mars Transportation[3]	Commercial Cis-Lunar Transportation[4]
			3 Stage Arch to NRHO		2 Stage	Single Stage				
Timeframe	days to months	6 mo - 1 year	1 mission/yr	1 mission/yr	per mission	per mission	per mission	1 mission/yr	per year	per year
Demo/System Mass[5]	10's kg to low 100's kg	1 mt O_2 Pilot 1.3 – 2.5 mt Ice Mining	1400 to 2200 kg	2400 to 3700 kg				Not Defined	Not Defined	29,000 to 41,000 kg
Amount O_2	10's kg	1000 kg	4,000 to 6,000 kg	8,000 to 10,000 kg	10,000 kg	33,000 kg	32,000 kg	30,000 to 50,000 kg	185,000 to 267,000 kg	400,000 to 2,175,000 kg
Amount H_2	10's gms to kilograms	125 kg		1,400 to 1,900 kg	2,000 kg	7,000 kg	Methane Fuel	5,500 to 9,100 kg	23,000 to 33,000 kg	50,000 to 275,000 kg
Power for O_2 in NPS	100's W	5 to 6 KW	20 to 32 KW	40 to 55 KW				N/A	N/A	N/A
Power for H_2O in PSR	100's W	~2 KW		~25 KW				14 to 23 KW		150 to 800 KW
Power for H_2O to O_2/H_2 in NPS		~6 KW		~48 KWe				55 to 100 KWe		370 to 2,000 KWe

NPS = Near Permanent Sunlight

PSR = Permanently Shadowed Region

[1]Estimates from rocket equation and mission assumptions

[2]Estimates from J. Elliott, "ISRU in Support of an Architecture for a Self-Sustained Lunar Base "

[3]Estimate from C. Jones, "Cis-Lunar Reusable In-Space Transportation Architecture for the Evolvable Mars Campaign"

[4]Estimate from "Commercial Lunar Propellant Architecture" study

[5]Electrical power generation and product storage mass not included

[6] APL Lunar Surface Innovation Consortium Suppy-Demand Workshop, 9/17/2020

- Table uses best available studies and commercial considerations to guide development requirements/FOMs
- Table provides rough guide to developers and other surface elements/Strategic Technology Plans for interfacing with ISRU

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

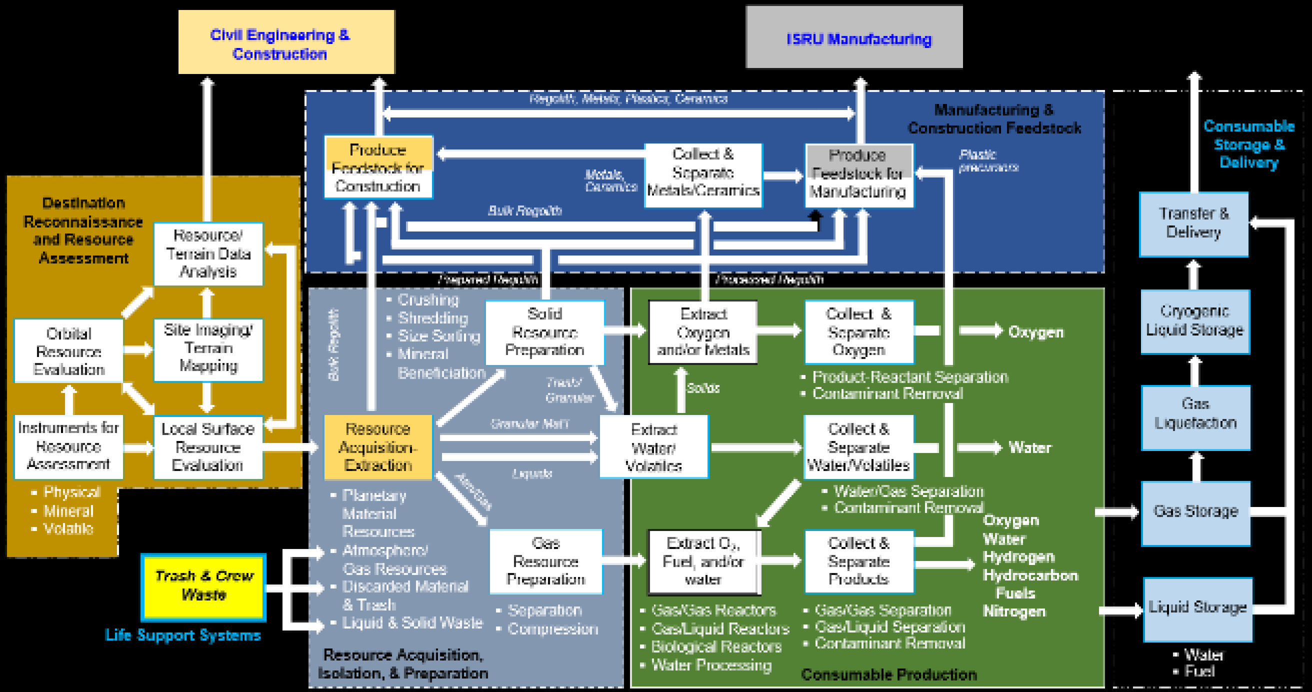
Resource Processing for Production of Manufacturing and Construction Feedstock

- 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

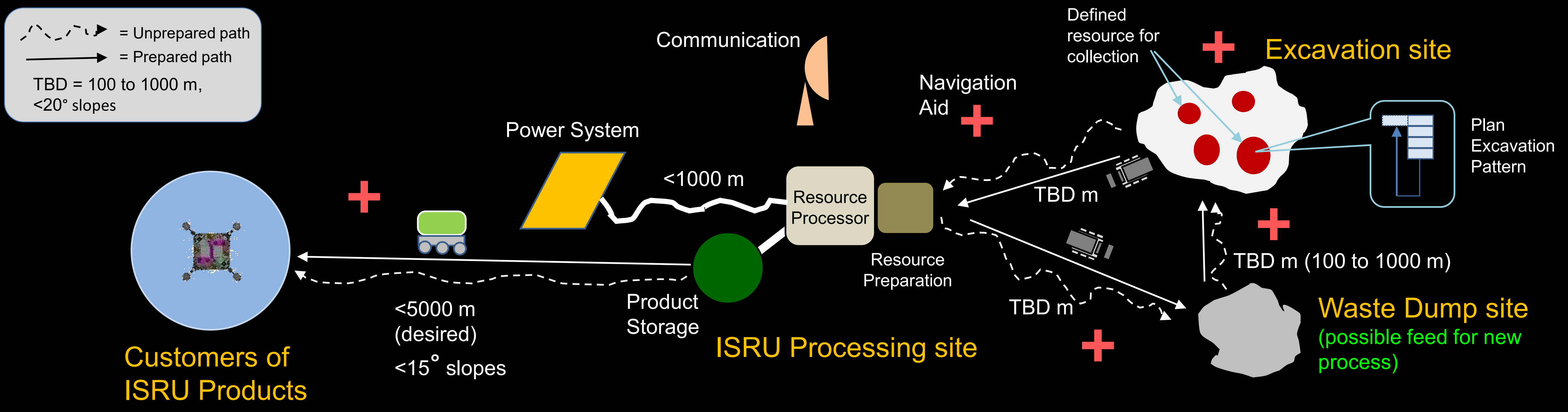
Cross Cutting

- 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 with Autonomous Excavation, Construction, & Outfitting (AECO)
  - Destination Reconnaissance
  - Resource Excavation & Delivery
  - Construction Feedstock Production



Lunar ISRU System and Concept of Operations



- Resources mapped, site locations defined, and excavation plan established before operations begin
- Multiple excavators operate between the Excavation site, ISRU Processing site, and Waste Dump site ahead of processing rate
- ISRU Processing systems should be modular for growth with robotic/human maintenance and repair capabilities
- Product transfer from ISRU to customer(s) occurs periodically. Minimum losses of cryogenic fluids desired
- Navigation and communication capabilities support semi to full autonomous operations.
- Initial operations over unprepared surfaces. Prepared paths created over time to minimize wear and increase efficiency
- Power systems may be dedicated to ISRU operations. Type of power transmission will be a function of distance and overall processing economics

NASA Blueprint Objectives
Objectives tied to ISRU Implementation

Transportation and Habitation Objectives

TH-3: Develop systems to allow crew to live and operate safely on the lunar surface and lunar orbit for extended periods of time with scalability to continuous presence to visit areas of interest for scientific research, conduct Mars analog activities, support industrial utilization, and conduct utilization activities.

TH-7: Develop systems for crew to live, operate, and explore on the Martian surface to address key questions with respect to science and resources.

Lunar and Mars Infrastructure Objectives

LI-3: Demonstrate autonomous construction, precision landing, surface transportation, industrial scale ISRU and Advanced Manufacturing capabilities in support of future continuous human lunar presence and a robust lunar economy.

LI-4: Demonstrate technologies supporting cislunar orbital/surface depots, construction and manufacturing maximizing the use of in-situ materials, and support systems needed for continuous human/robotic presence.

Operations Objectives

OP-3: Characterize accessible lunar resources and gather scientific research data to satisfy science and technology objectives on successive missions.

OP-8: **Demonstrate the capability to find, service, upgrade, or utilize instruments and equipment from robotic landers or previous human missions on the surface of the Moon and Mars.**

OP-11: Demonstrate the capability to use commodities produced from planetary surface or in-space resources to reduce the mass required to be transported from Earth.

Science Objectives

LPS-1: Conduct in-situ studies of planetary processes (Differentiation, Impact, Volatiles, Volcanism and Tectonism) to understand planet formation. .

LPS-2: Collect fundamental data to understand volatile cycles (comet impacts, solar wind hydrogen, primordial, permanently shadowed regions), including types/extent of chemicals present.

NASA Lunar ISRU Objectives

Lunar ISRU To Sustain and Grow Human Lunar Surface Exploration

- Lunar Resource Characterization for Science and Prospecting
  - Provide ground-truth on physical, mineral, and volatile characteristics – provide geological context;
  - Test technologies to reduce risk for future extraction/mining
- **Mission Consumable Production (O_2, H_2O, Fuel):**
- Learn to Use Lunar Resources and ISRU for Sustained Operations
  - *In situ* manufacturing and construction feedstock and applications

Lunar ISRU To Reduce the Risk and Prepare for Human Mars Exploration

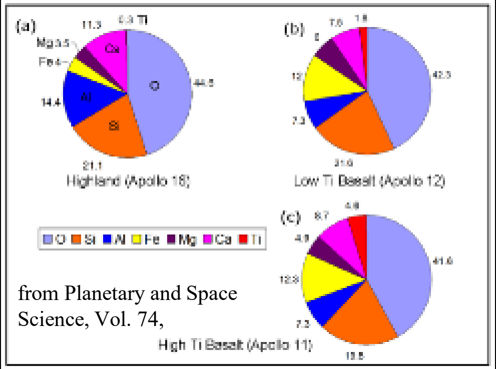
- Develop and demonstrate technologies and systems applicable to Mars
- Use Moon for operational experience and mission validation for Mars; Mission critical application
  - Regolith/soil excavation, transport, and processing to extract, collect, and clean water
  - Pre-deploy, remote activation and operation, autonomy, propellant transfer, landing with empty tanks
- Enable New Mission Capabilities with ISRU
  - Refuelable hoppers, enhanced shielding, common mission fluids and depots

Lunar ISRU To Enable Economic Expansion into Space

- *SPD-1: Reinvigorating America's Human Space Exploration Program*
  - Promote International Partnerships
  - Promote Commercial Operations/Business Opportunities (Terrestrial and Space)
- Support/promote establishment of reusable/commercial transportation with propellant depots/ISRU propellants
- Promote spin-offs to make terrestrial industry more efficient/profitable

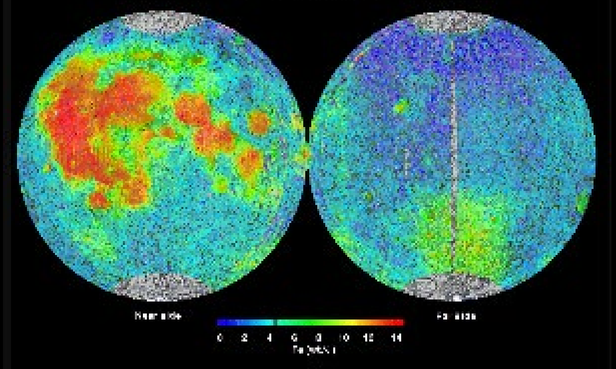
Lunar Resources for Commercial and Strategic Interests

Elements in Lunar Regolith

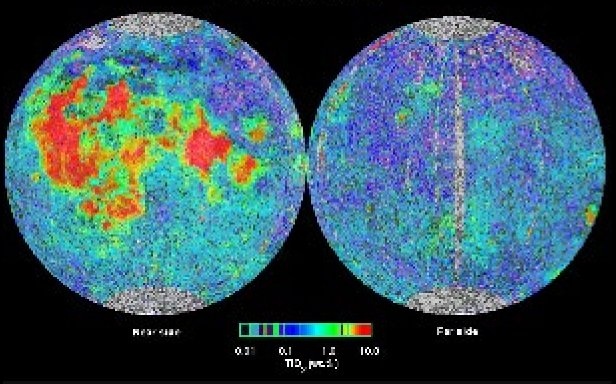


from Planetary and Space Science, Vol. 74,

***Clementine* Iron Map of the Moon**
Equal Area Projection

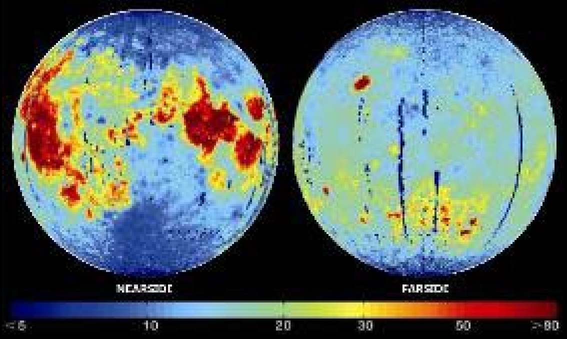


***Clementine* Titanium Map of the Moon**
Equal Area Projection

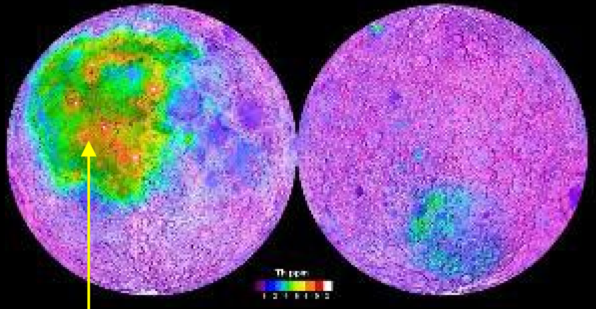


Estimated concentration of 3He

(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,



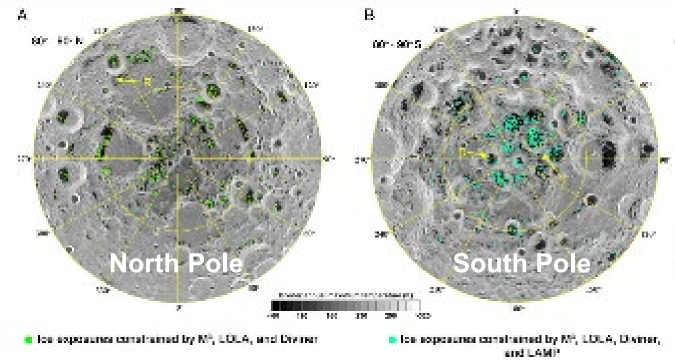
Indication of where KREEP is
(Procellerum KREEP Terrane)
Prettyman et al., 2006;

Rare Earth Elements

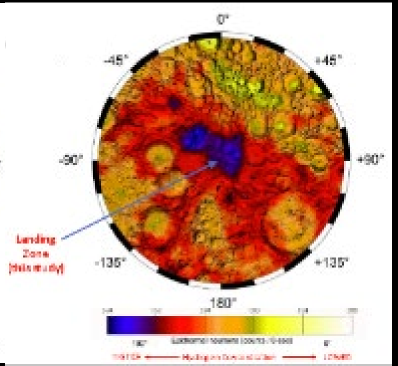
		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Pr	ppm	13	---	7	9.2
Nd	ppm	63	40	39	41.5
Sm	ppm	21	14	13	7.05
Eu	ppm	2.2	1.9	1.7	2
Gd	ppm	27	20	15	6.2

Evidence of Water & Volatiles at the Lunar Poles

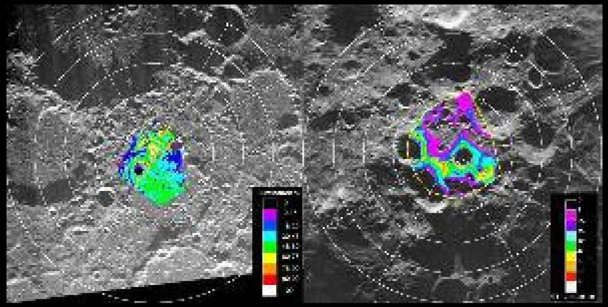
Spectral Evidence (Li, et. al)



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

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

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

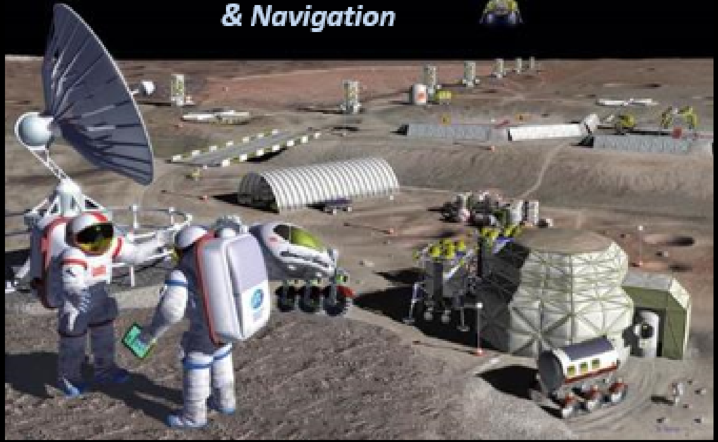
Maintenance & Repair

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

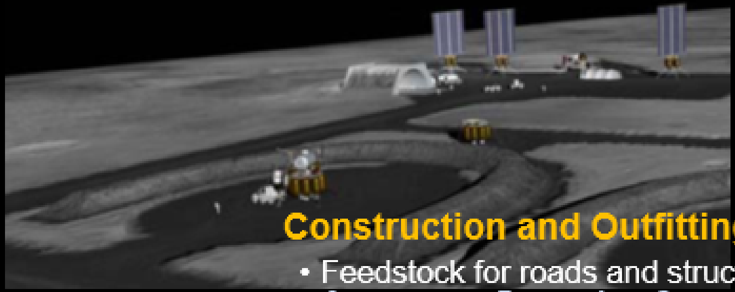


Living Quarters & Crew Support Services
- Water, O_2, H_2, Gases (S)
- Trash/waste (P)
- Nutrients(S)

In situ Instruments/Sensors
Autonomous Systems
Adv. Thermal Management

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

Polar Ice Resource Assessment – Current Related* Development (1 of 2)

*Not all funded efforts are designated as ISRU

- **Acquire Icy Regolith Samples**
  - FLEET: Fundamental Regolith Properties Project - Bulk water stability – NASA GRC
  - Characterization of Lunar Polar Volatiles for Curation and ISRU – NASA JSC – Active
  - ColdARM – JPL – GCD
  - Trident Auger – Honeybee Robotics – VIPER
  - Honeybee PVEx Drill – SSEVI RESOURCE project
- **Instruments for Physical/Geotechnical Characterization**
  - Material Characterization while Drilling on Lunar/Martian Surface – ESI with CSM – Completed
  - Moon-Mars Ice Challenge – NASA LaRC
  - Percussive Hot Cone Penetrometer and GPR – Mich Tech – LuSTR
  - Soil Properties Assessment Resistance & Thermal Analysis (SPARTA) – JPL - SMD
- **Instruments for Mineral/Elemental Characterization**
  - Fundamental Regolith Properties Project - Bulk water stability – NASA GRC
  - *Recent 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
  - Locating and Identifying Lunar Volatiles using Heat and Mass Transfer – CSM – NSTGRO
  - WRANGL3R - Water Regolith ANalysis for Grounded Lunar 3d Reconnaissance (mini drill and LIBS)- Univ of Texas El Paso – LuSTR

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	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
X					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

Polar Ice Resource Assessment – Current Related* Development (2 of 2)

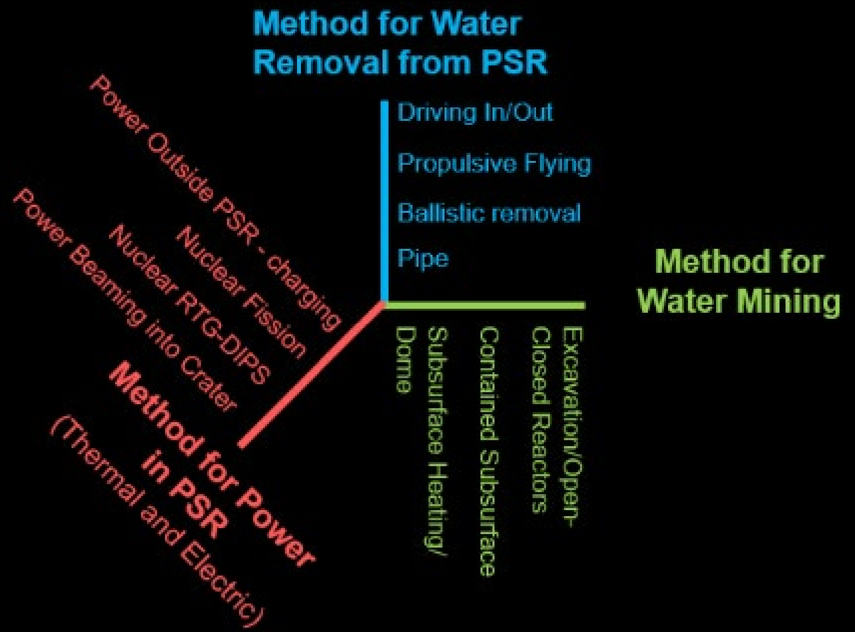
*Not all funded efforts are designated as ISRU

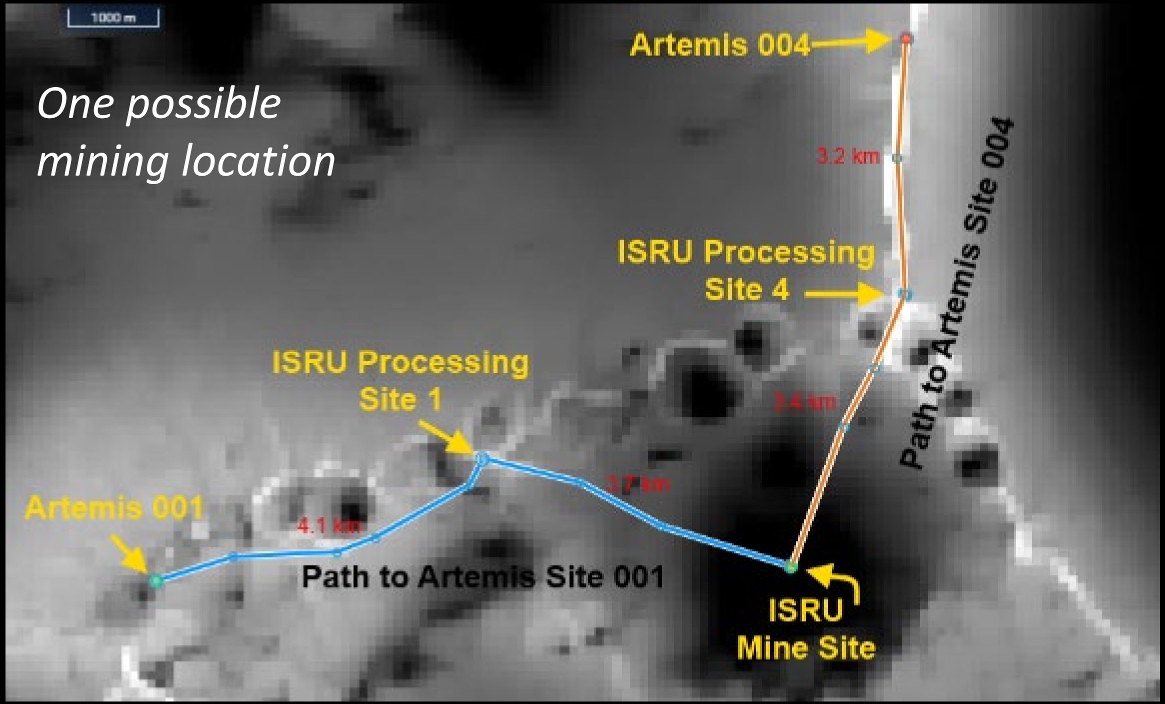
- **Mobility and Instruments for Resource Assessment**
  - L-Puffer/ Cooperative Autonomous Distributed Robotic Explorers (CADRE) – JPL; Mini-rover w/ TBD instruments
  - MoonRanger – SMD DALI; Mini-rover w/ camera (2022)
  - NeuRover – SBIR Phase II; Mini-rover w/ neutron spectrometer
  - Robotic Technologies Enabling the Exploration of Lunar Pits – Phase III Carnegie Mellon
  - Mobile Autonomous Prospecting Platform (MAPP) – Lunar Outpost (*Not NASA funded*)
  - High TRL Rover Lidar – NASA GSFC
  - Lunar DEM, Mapping, Modeling, and Validation (LuNaMaps)
  - Micro-Nova hopper with camera

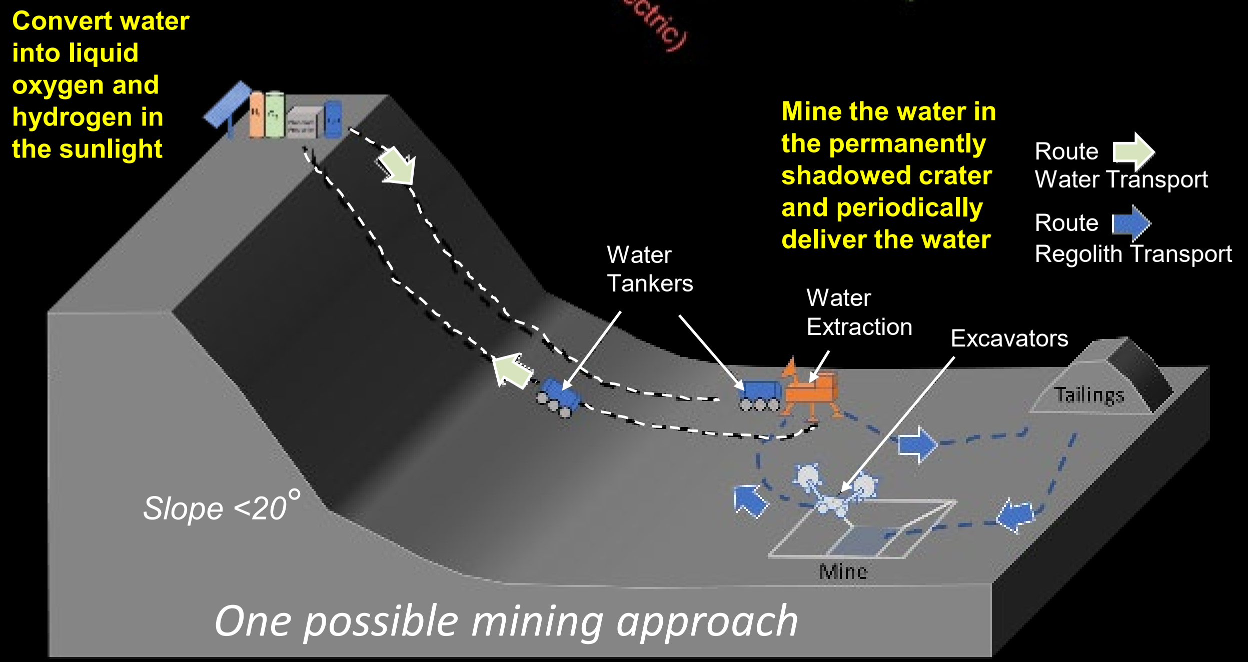
Polar Ice/Water Mining - Overview

**Assumes customers for water & O_2/H_2 are outside of the PSR*

- **Three main drivers for Water Mining Architecture viability**
  - Method of Water removal from Crater*
  - Method of Power delivery into Crater
  - Method of Water Mining
- **Application of mining technologies are highly dependent on:**
  - Resource Depth Access: How deep the water resource can be for a given concept to work.
  - Spatial Resource Definition: How homogenous is the resource
  - Resource Geotechnical Properties: How hard and porous is the icy regolith
  - Volatiles Retention: How much of the volatiles are captured vs lost to the environment.
  - Material Handling: How much interaction is required with the regolith.



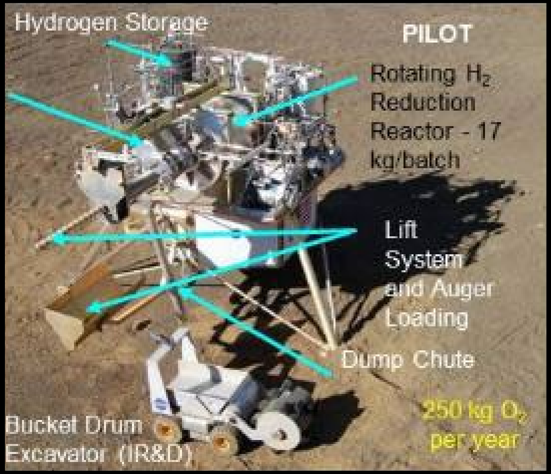


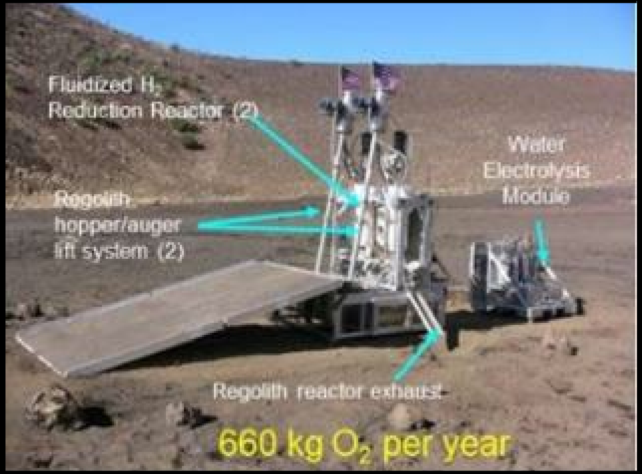


Oxygen from Regolith – Overview/Past Development (Constellation)

- **Lunar regolith is >40% oxygen (O2) by mass**
  - Four primary mineral types on the Moon: Ilmenite, Pyroxene, Olivine, and Anorthite
  - Ilmenite and pyroclastic glasses are the easiest lunar materials to reduce/extract O_2
  - Lunar polar regolith primarily Highland-type: >75% anorthite, iron poor
- **Over 20 processes have been identified to extract the oxygen**
  - Several have been evaluated in the lab to TRL 3 at subscale
  - As processing temps increase, O2 yield increases, and technical and engineering challenges increase
  - **Work during the Constellation Program focused on three processes**
    - Hydrogen reduction: 'low' temperature, low yield (1 to 5 wt%), high TRL
    - Carbothermal reduction: 'higher' temperature, medium yield (5 to 15 wt%), medium TRL
    - Molten regolith electrolysis: 'high' temperature, high yield (>20 wt%), low TRL
    - ❖ Note: Other technologies were also evaluated under internal and SBIR contracts
- **Two processes developed to TRL 4-5 at human mission relevant scale**

O_2 Cryo Tank





Polar Ice/Water Mining – Current Development

Three main Polar Ice/Water Mining Methods under development/consideration:

1. **Excavation/Acquisition and Processing Reactor**
   - Lunar Auger Dryer ISRU (LADI) - NASA JSC – GCD
   - Aqua Factorem (Ice Crystal Sifting) – UCF – NIAC Phase I – completed
   - Lunar Ice Mining Using a Heat-Assisted Cutting Tool – Sierra Lobo - SBIR Phase I – completed
   - Lunar Water Extraction Techniques and Systems – TransAstra – SBIR Phase I
   - Mobile Water Extractor – GCD – GRC

2. **Subsurface Heating - Contained**
   - PVEx – Honeybee Robotics – SBIR Phase II/SSERVI RESOURCE project
   - Thermal Management for Lunar Ice Miners (w/ PVEx) - Advanced Cooling Technologies – SBIR Phase I/II

3. **Subsurface Heating/Ablating and Volatile Release Capture**
   - Ablative Arc Mining for In-Situ Resource Utilization – UT El Paso - LuSTR
   - Lunar Polar Propellant Mining Outpost – TransAstra – NIAC Phase II
   - Thermal Mining of Ices on Cold Solar System Bodies – CSM – NIAC Phase I - completed

Oxygen (Metal) from Regolith - Current Development

Oxygen Extraction Methods under development:

1. Carbothermal Reduction w/ Methane
    - Carbothermal Reduction Reactor Design – Sierra Nevada Corp (SNC) – 2 SBIR Phase IIIs, and COPR Tipping Point
    - CaRD - Carbothermal Reduction Demonstration – GCD JSC
2. Molten Regolith Electrolysis (MRE)
    - Molten Regolith Electrolysis - Lunar Resources – NASA SBIR Phase I/II and NSF SBIR Phase II
    - Molten Regolith Electrolysis Tech Maturation – KSC – GCD and ECI
3. 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
4. Plasma Hydrogen Reduction
    - Plasma Hydrogen Process – KSC – CIF
5. Moon to Mars Oxygen and Steel Technology (CO/H_2 Reduction) - Pioneer Astronautics - SBIR Phase II Sequential
6. Carbothermal/Vapor Pyrolysis with Solar Concentrator – Blueshift - SBIR Phase I – Completed

Not funded by NASA

- Molten Regolith Electrolysis – Blue Origin
- Vapor Pyrolysis – Terraxis
- Molten Salt Electrolysis – Airbus and Thales Alenia

Water Processing – Current Related* Development

*Not all funded efforts are designated as ISRU

- **Three main Water Electrolysis technologies under development/consideration:**
  1. Proton Exchange Membrane (PEM)
     - IHOP PEM Water Electrolysis/Clean-up – Paragon – BAA
     - Regenerative Fuel Cell Project – GRC – GCD/TDM
     - Lunar Propellant Production Plant (LP3) – Skyre –TP
     - Static Vapor Feed Electrolysis (SVFE) for ISS - Giner
  2. Solid Oxide Electrolysis (SOE)
     - Lunar Ice Processing – CSM/OxEon - TP
     - Redox Tolerant Cathode for Solid Oxide Electrolysis Stacks – OxEon - Phase II SBIR
     - Production of Oxygen and Fuels from In-Situ Resources on Mars – OxEon – BAA
  3. Alkaline: Clean or Dirty Water
     - Dirty Water Alkaline Electrolysis – Teledyne - BAA - Completed
     - Advanced Alkaline Reversible Cell – pH Matter - ACO
     - BRACES– Bifurcated Reversible Alkaline Cell for Energy Storage (clean water) – pH Matter – TP

- **Water Capture and Cleanup under development/consideration**
  - Lunar water simulant definition – NASA - CIF and Simulant Project
  - Fundamental Regolith Properties, Handling, and Water Capture – NASA – GCD
  - ICICLE - ISRU Collector of Ice in a Cold Lunar Environment-IHOPP –Paragon - SBIR Phase I/II
  - IHOP PEM Water Electrolysis/Clean-up – Paragon – BAA
  - Thermal Management for Lunar Ice Miners (w/ PVEx) - Advanced Cooling Technologies – SBIR Phase II
  - Water vapor capture and regenerative water cleanup – SSERVI RESOURCE project

Regolith Processing Support – Current Related* Development (1 of 2)

*Not all funded efforts are designated as ISRU

- **Regolith sealing, transfer, sorting, and beneficiation**
  - FLEET: Fundamental Regolith Properties Project– NASA GRC
  - Regolith Valve – NASA GRC
  - Dev of Dust-Tolerant Seals & Performance Database – NASA
  - Motors for Dusty & Extremely Cold Environments (MDECE) and Bulk Metallic Glass Gears (BMGG)
  - MMOST – sorting and mineral beneficiation –Pioneer Astronautics SBIR Phase II
  - Regolith Beneficiation for Production of Lunar Calcium and Aluminum – Uni of Missouri-Rolla LuSTR
- **Deployable large scale solar collection/thermal energy transfer for regolith melting**
  - Multi-dish concentrator w/ fiber optic delivery – PSI SBIR Phase II.
  - Inflatable solar concentrator and mirror/lens assembly – for APIS NIAC Phase II
  - Lightweight Low Stow Volume Solar Concentrator for Lunar ISRU – L'Garde SBIR Phase I
- **Reactant/Product Separation, Regeneration, and Recycling**
  - Lunar ISRU Contaminant Tolerant Scroll Vacuum Pump – AirSquared SBIR Phase I
  - Highly Efficient H2 Separation Module for Space O_2 Recovery System - Bettergy Corp SBIR Phase II
  - Methane/Hydrogen Microchannel Separator – BAA with Skyhaven - Completed
- **Process monitoring and sensors**
  - Laser Spectrometers for Impurity Analysis in ISRU Gas Streams – JPL GCD
- **Motors/Gears**
  - Motors for Dusty and Extremely Cold Environments (MDECE) – GCD
  - Bulk Metallic Glass Gears (BMGG) - GCD

Regolith Processing Support – Current Related* Development (2 of 2)

*Not all funded efforts are designated as ISRU

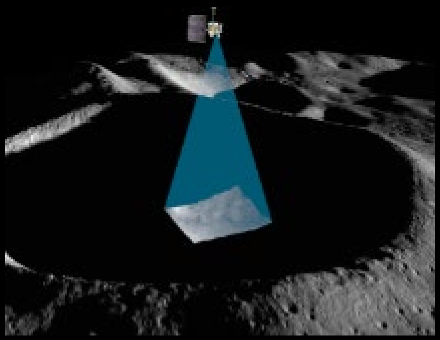
- **Facilities & Simulants**
  - NASA Simulant Project: Figures of Merits, forecast survey, advice/portal, simulant characterization (with APL), and simulant production and storage (NU-LHT from USGS, new OB1A, GreenSpar anorthosite, BP-1, Exolith, Off Planet, CSM)
  - JSC Dirty Environment Facility: 15 ft dia (4.5 m dia). Thermal/vac chamber with regolith and dust deposition, regolith prep and checkout areas, ambient dust/regolith testing bin – operational by end of 2022
  - MSFC V20 Environmental Facility 20 ft. diameter x 28 ft. long (6.1m dia. x 8.5m long): Modifications to allow for regolith and dust approved.

NASA Lunar Polar Science & Resource Assessment Missions
Current & In Development

Orbital Missions

Lunar Reconnaissance Orbiter

ShadowCam on Korean Pathfinder Lunar Orbiter



Lunar Trailblazer

Artemis I Cubesats

Lunar IceCube

Lunar Flashlight

LunaH-Map

Surface Missions

- **2022** Intuitive Machine CLPS mounted payload to detect volatiles at 1-m depths
- Instruments include:
  - Mass Spectrometer Observing Lunar Operations (MSolo)
  - The Regolith and Ice Drill for Exploring New Terrain (TRIDENT)

PRIME-1

VIPER

- **2023** Astrobotics CLPS delivered to South Pole
- Measure volatiles at the lunar poles and acquire new key data on lateral and vertical distribution
  - Neutron Spectrometer System (NSS)
  - Near Infrared Spectrometer (NIRVSS)
  - Msolo Mass Spectrometer
  - TRIDENT Drill
- Build lunar resource maps for future exploration sites
  - Long duration operation (months)
  - Traverse 10's km