EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

In Situ Resource Utilization (ISRU) Envisioned Future Priorities

Luxembourg Space Week

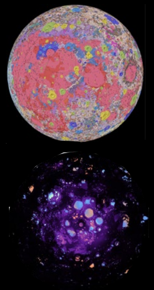
May. 3-5, 2022

Gerald (Jerry) Sanders | ISRU System Capability Lead – STMD | gerald.b.sanders@nasa.gov
Julie Kleinhenz | ISRU System Capability Deputy – STMD | julie.e.kleinhenz@nasa.gov

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

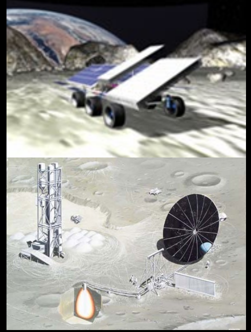


- Lunar resources mapped at meter scale for commercial mining
- 10's of metric tons of commodities per year for initial goal commercial usage
- Scalable to 100's to 1000's metric tons per year

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

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

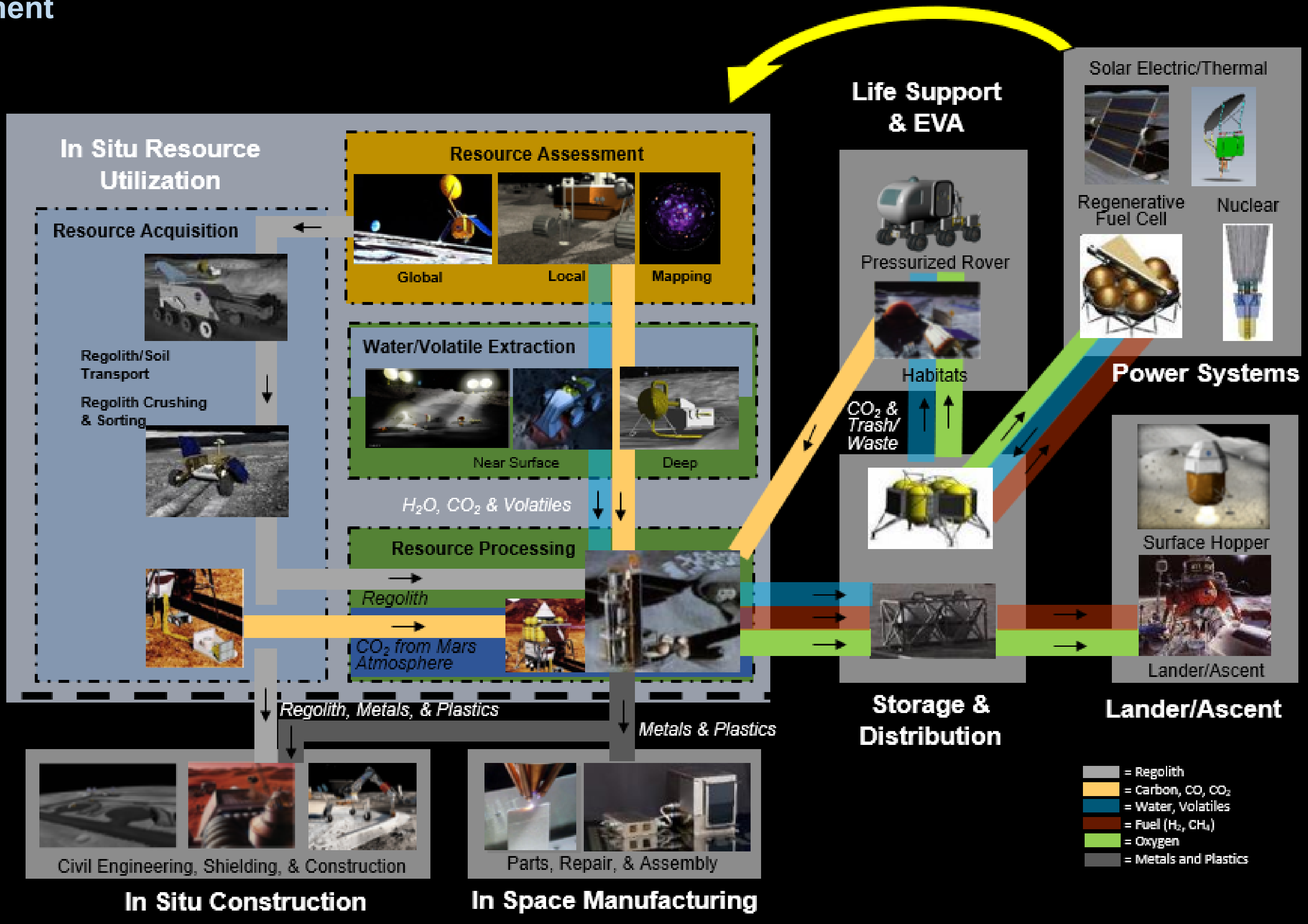
Chemical, thermal, electrical, and or biological conversion of acquired resources and intermediate products into

- 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**

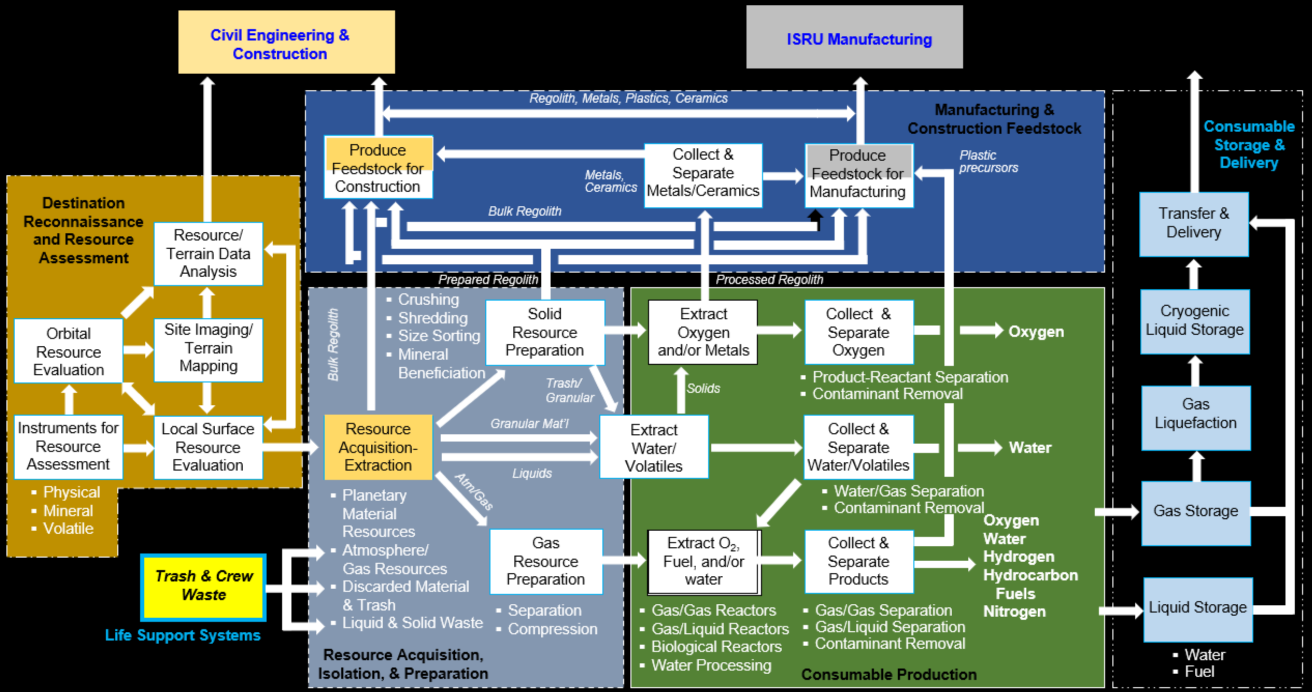


*Commodities are items and consumables that can be eventually sold

ISRU Functional Breakdown And Flow Diagram

Destination Reconnaissance and Resource Assessment	Resource Acquisition, Isolation, and Preparation	Resource Processing for Production of Mission Consumables	*Resource Processing for Production of Manufacturing and Construction Feedstock*	*Cross Cutting*
• Site Imaging/Terrain Mapping • Instruments for Resource Assessment • Orbital Resource Evaluation • Local Surface Resource Evaluation • Resource/Terrain/Environment Data Fusion and Analyses	• Resource Excavation & Acquisition • Resource Preparation before Processing • Resource Transfer • Resource Delivery from Mine Site and Removal	• 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	• 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	• 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



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

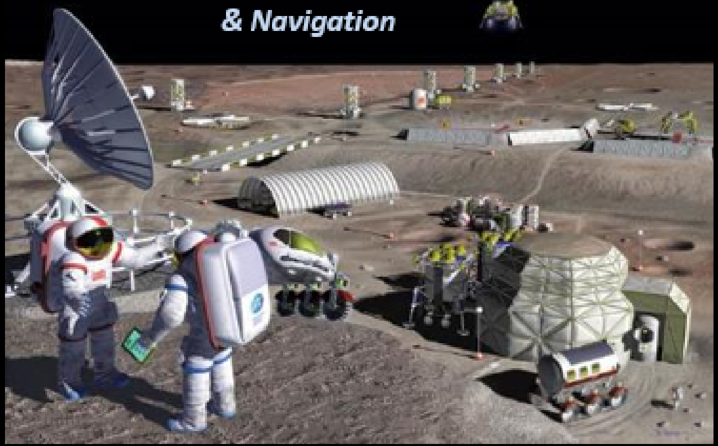
Maintenance & Repair

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

In Space/Surface Manufacturing

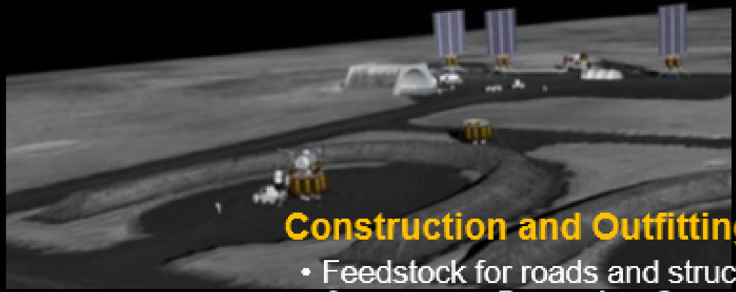
ISRU

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



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

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

Resources

Lunar Regolith

- **Highland/Polar area**
  >75% Anorthite, Pyroxene, 7% Olivine
- Mare – Basalt
  15-20% Plagioclase, 15-24% Pyroxene, 3-4% Olivine, 2-10% Ilmenite, 45-53% Agglutinate glass

Minor Constituents

- Pyroclastic Glass
- KREEP (Potassium, Rare Earth Elements, Phosphorous) and Radioactive Elements (Th, U)
- Solar Wind Implanted Volatiles (parts per million)

Polar Water/Volatiles

- LCROSS impact estimated **5.5 wt%** water with other volatiles present in Cabeus crater
  - Hydrogen-bearing (H_2O, H_2, H_2S, NH_3, OH)
  - Organics (CO, C_2H_4, CO_2, CH_3OH, CH_4)
  - Metals (Ca, Hg, Mg, SO_2)

Initial Commodities

- **Bulk/Refined Regolith**
- Reduced Oxides/Slag
- **Metals – Raw alloys**
- Silicon – Raw Silica
- **Oxygen**
- Rare Earth Elements
- Radioactive Materials
- Potassium/Phosphorus
- Hydrogen
- Helium/Helium-3
- Carbon/Carbon Oxides
- Nitrogen/Ammonia/Sulfur
- **Water (& O_2/H_2)**

Refined Products

- Metals & Ceramics for Manufacturing, Construction, & Energy
  (Metal wire/bars/powder, Silicon, Ceramic powder, bricks/slabs)
- Polymers,
  (Resins, plastics, composites)
- Propellants & Fuel Cell Reactants
  (Oxygen, Hydrogen, Methane, Kerosine, Hydrogen Peroxide)
- Life Support & Thermal Control
  (Oxygen, Nitrogen, Hydrogen, Water, Ammonia)
- Nutrients & Plant Growth

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 (SMD and ESDMD)
  - 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

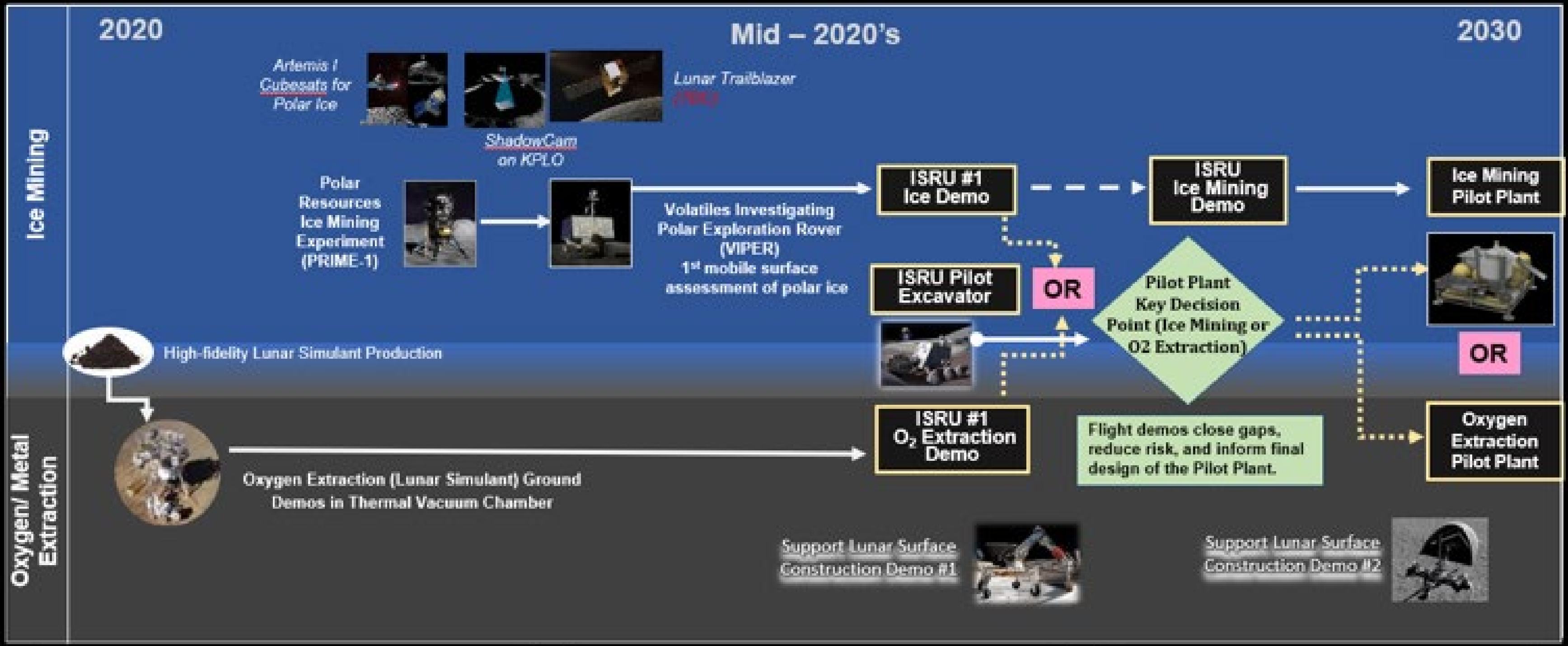
- **Perform End-to-End ISRU Production of Commodities & Demonstrate Usage**
  - Production at sufficient scale to eliminate risk of Full-scale system
  - Initially use ISRU-derived commodity in non-mission critical application; examples include non-crewed ascent vehicle or hopper, extra fuel cell power, 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**



Full-scale implementation & Commercial Operations
(see next chart)

Reconnaissance, Prospecting, Sampling
Sub-system Demonstrations: Investigate, sample, and analyze the environment for mining and utilization.

Resource Acquisition & Processing
Demonstrations for extraction and processing of raw materials for mission consumables production and storage.

Pilot Consumable Production
Sustainable Exploration: Scalable Pilot Systems producing consumables from in-situ resources in order to support sustained human presence.

- 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

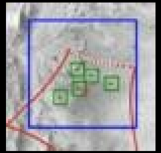
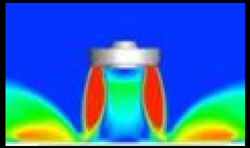
Near-Term Envisioned Future:

Evolve from STMD Demonstrations to Sustained Lunar Surface Operations

STMD Leads *Individual* Technology Development and Flight Demonstrations


ISRU Demo & Pilot Plant

ISRU Pilot Excavator

Precision Landing (SPLICE) & Plume Surface Interaction

Cryo Fluid Management TP & Flight Demos

Autonomous Robotics, LIDAR, and Navigation

In Situ Construction Demos

Vertical Solar Array Technology (VSAT)

Power Beaming

40 KWe Nuclear Reactor Demo

Regenerative Fuel Cell Power Demo

HEOMD Evolves STMD Capabilities into Sustained Artemis Base Camp Infrastructure and Commercial Operations

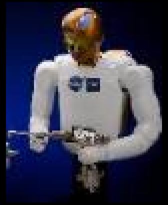
Large Scale Power Generation & Distribution


Complex, Multi-Element ISRU Operations

Landing Pad & Infrastructure Construction


Cryogenic Consumables & Propellant Depots

Human and Robotic Maintenance & Repair

Offloading, Deployment, and Repurposing

Lander, Habitat, and Surface Vehicle Servicing

NASA ISRU Capability State of the Art and Current Work

Resource Assessment – Flight Development (TRL 4-6)
- Multiple instruments under development by SMD and STMD for resource collection and assessment
- Instruments to be flown on CLPS missions – PRIME-1 and VIPER for lunar ice characterization

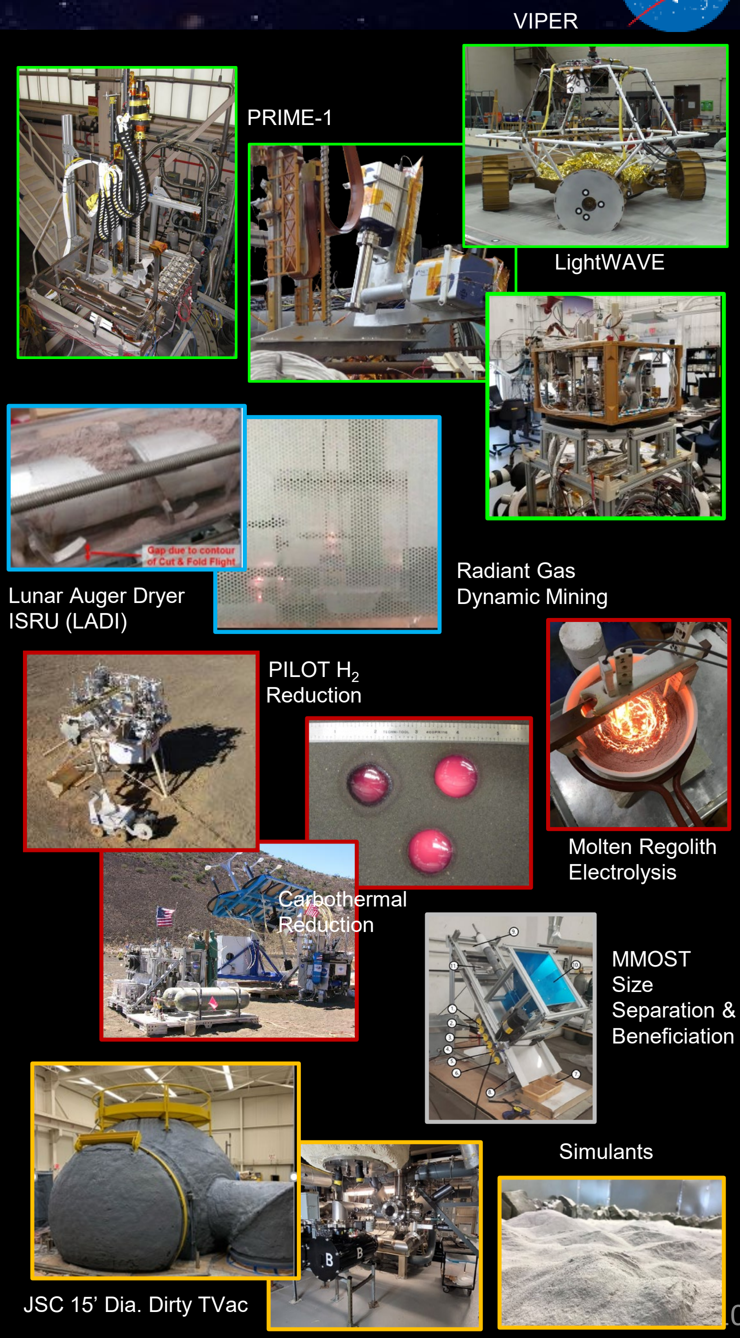
Water Mining – Proof of Concept (TRL 2/3)
- 3 mining approaches and 6 water extraction technologies under development
- Challenges: Space Robotic, Break the Ice Lunar

Oxygen Extraction from Regolith – Engineering Breadboards/Field Test Units (TRL 4/5)
- Two Hydrogen Reduction systems built and tested at Pilot scale; terrestrial operations, non-flight mass/power, mare regolith, days/weeks operation (2008)
- Carbothermal Reduction system with solar concentrator built and tested as Sub-Pilot scale; terrestrial operations, mare regolith, non-flight mass/power, days/weeks operation (2010)
- Carbothermal & Hydrogen Plasma Oxygen extraction methods now reducing Highland simulants under laboratory conditions (TRL 3)

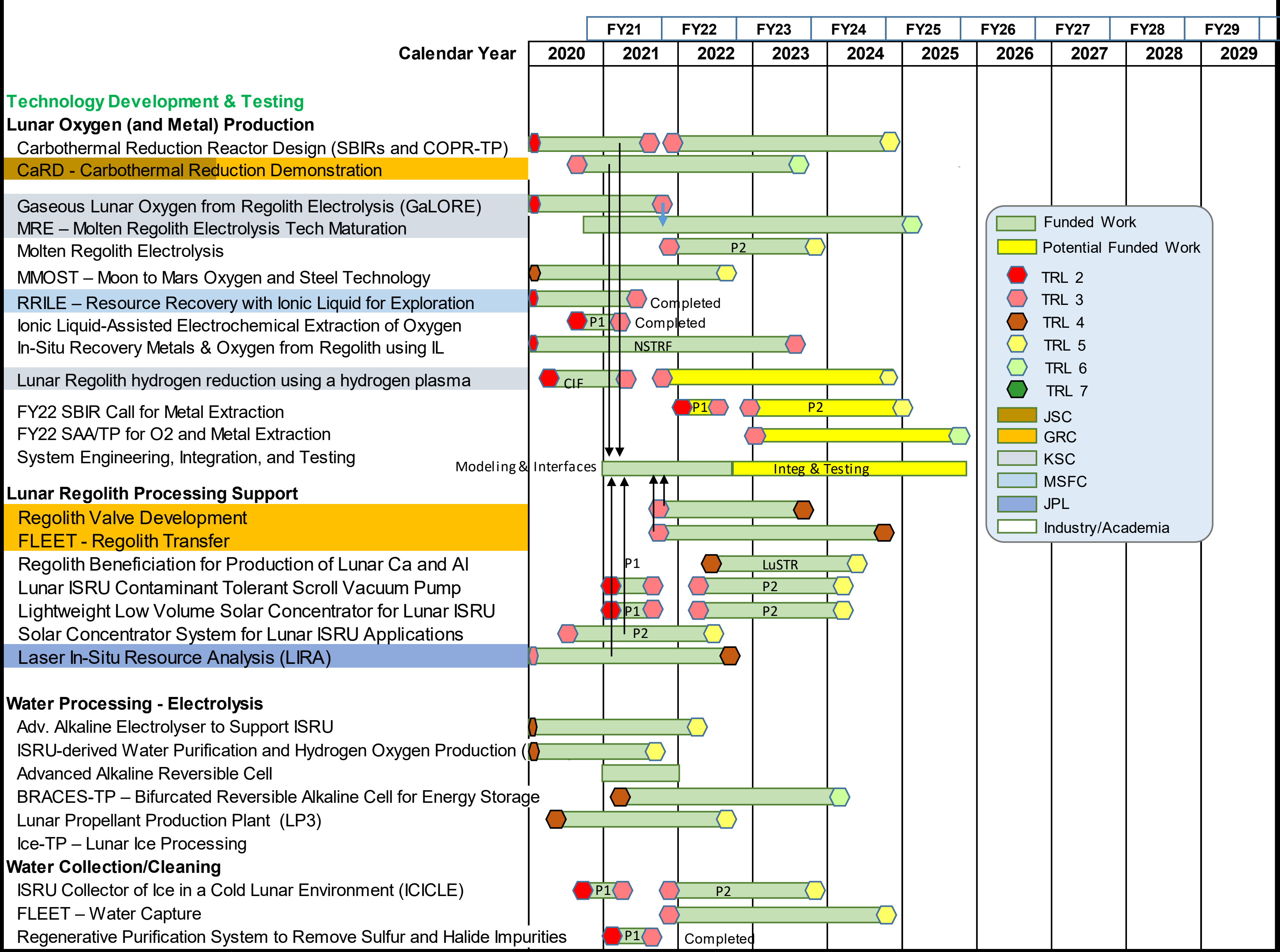
Oxygen/Metal Extraction from Regolith – Laboratory Proof of Concept
- Laboratory type/scale hardware: Molten Regolith Electrolysis (TRL 3/4); Ionic Liquid Reduction (TRL 2/3); International development of Molten Salt Electrolysis-ESA (TRL 3/4) and MRE-Israel (TRL 3/4)
- Bio-mining for oxygen/metal extraction (TRL 2/3)

Construction Feedstock (Low TRL: 2-4)
- Feedstock (blends of simulant and plastic) used in manufacturing & construction lab. demonstrations
- Mars concrete and soil/binders demonstrated: ACME & 3D Hab, Construction Centennial Challenge
- Size sorted lunar simulants being used for sintering construction tests
- Ilmenite beneficiation demonstrated on lunar-g aircraft
- 3D printer with simulant feedstock was tested on the ISS in the Additive manufacturing Facility
- Trash-to-Gas as start to conversion to fuels/plastics

Cross Cutting/System Level Resources
- 9 water electrolysis projects in 3 different types (PEM, SOE, Alkaline)
- NASA lunar simulant project initiated; Highland regolith simulant characterization & limited production
- External simulants available for purchase
- NASA Large dirty vacuum chamber almost ready at JSC; 2[nd] chamber at MSFC being modified

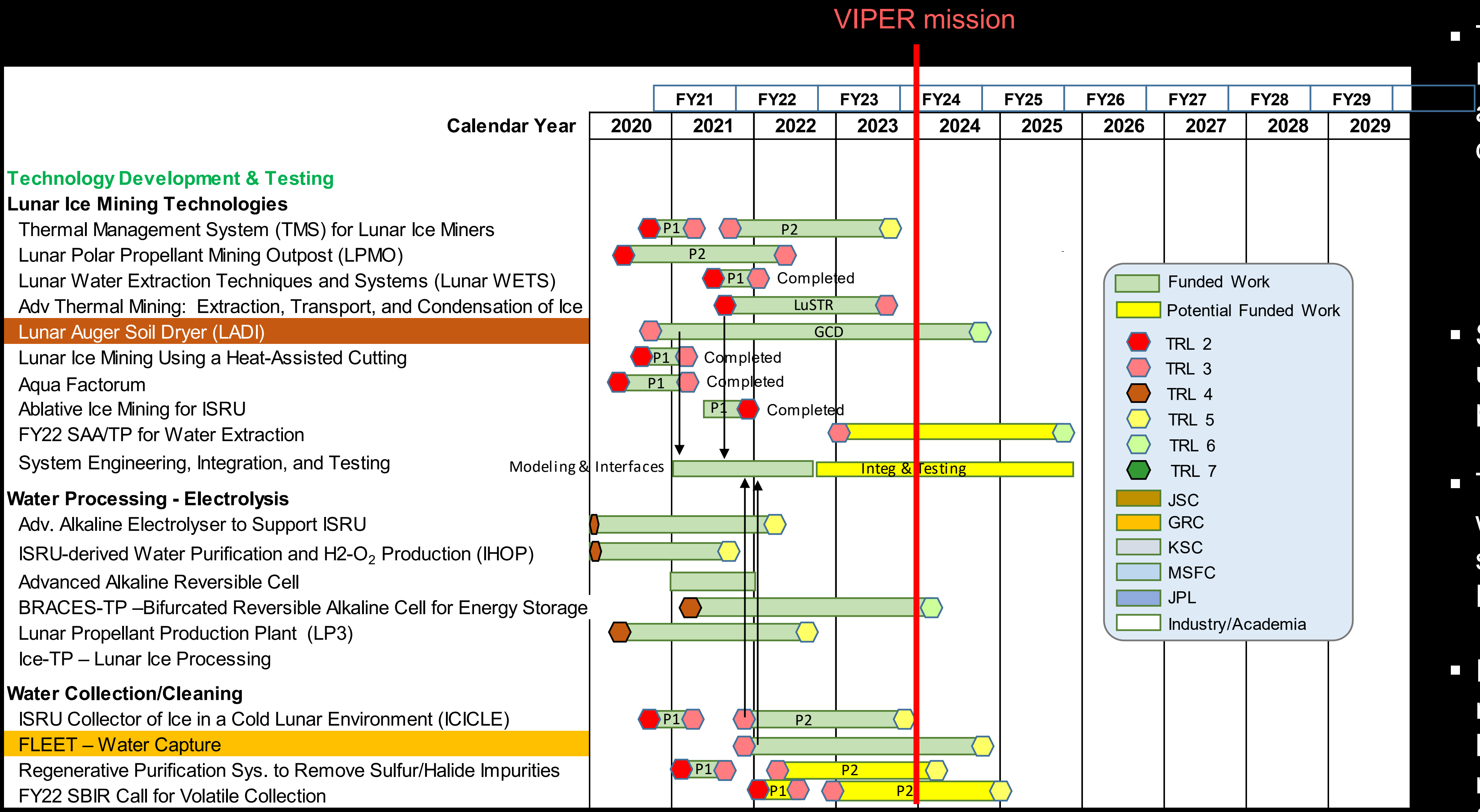


Current Oxygen-Metal from Regolith Development



- A significant amount of O_2 Extraction work has been accomplished to date with TRL 6 expected by 2023-25
- New work in O_2 and metal extraction expected from SBIR and Space Act Agreements
- NASA Centers are examining important technologies and generating critical data, especially with and for industry partners

Current Water Mining and Processing Development



- Three different Water Extraction/Mining approaches under development in parallel
  - Most work by industry and academia
- Significant work underway on water processing/electrolysis
- Technology readiness of water mining progressing slower than O_2 Extraction
- Information from VIPER mission expected to have major impact on icy regolith knowledge and focus of water extraction methods

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)

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
Yellow = Partially Covered; More Required
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

Backup

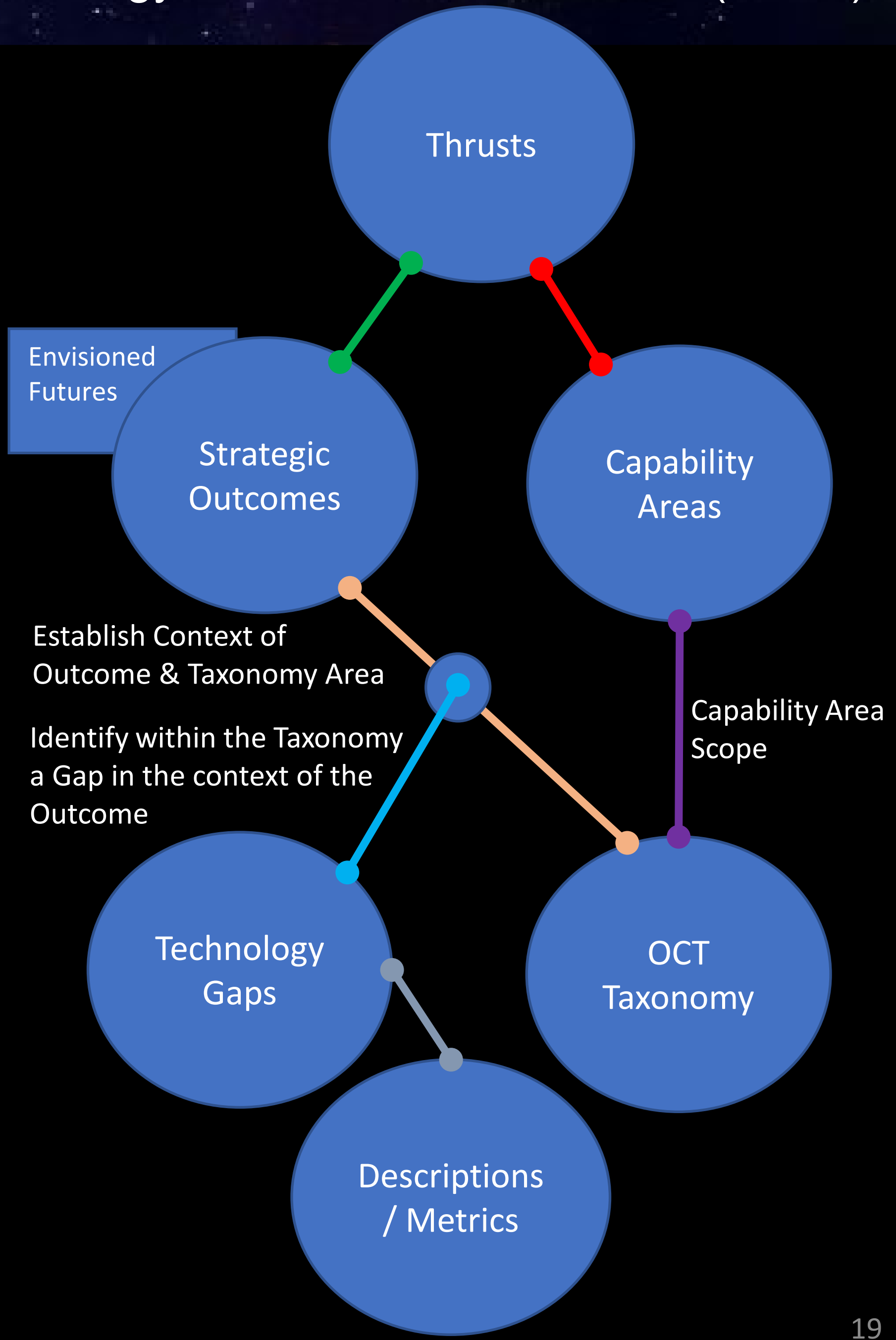
Acronyms

- ACME - Advanced Construction with Mobile Emplacement
- ACO - Announcement of Collaborative Opportunity
- Adv. - Advanced
- AECO - Autonomous Excavation, Construction, & Outfitting
- Al - Aluminum
- BAA - Broad Agency Announcement
- BIG Idea - Breakthrough, Innovation, and Game-changing
- BRACES - Bifurcated Reversible Alkaline Cell for Energy Storage
- Ca - Calcium
- CFM - Cryogenic Fluid Management
- C2H4 - Molecular formula for ethylene
- CH4 - Molecular formula for methane
- CH3OH - Molecular formula for methanol
- CIF - Center Innovation Fund
- CLPS - Commercial Lunar Payload Services
- CO - Molecular formula for carbon monoxide
- CO2 - Molecular formula for carbon dioxide
- COPR - Carbothermal Oxygen Production Reactor
- CY - Calendar Year
- Demo - Demonstration
- Dia - Diameter
- ECF - Early Career Faculty
- ESDMD – Exploration Systems Development Mission Directorate
- ESI - Early Stage Innovation
- EVA - Extra Vehicular Activity
- FLEET - Fundamental Regolith Properties, Handling, and Water Capture
- FY - Fiscal Year
- g - Gravity
- GRC - Glenn Research Center
- H2 - Molecular formula for hydrogen
- H2O - Molecular formula for water
- H2S - Molecular formula for hydrogen sulfide
- HEOMD –Human Exploration and Operation Mission Directorate
- Hg - Mercury
- ICICLE - ISRU Collector of Ice in a Cold Lunar Environment
- IHOP - ISRU-derived H2O Purification and H2-O2 Production
- IL - Ionic Liquid
- ISRU - In Situ Resource Utilization
- ISS - International Space Station
- JPL - Jet Propulsion Laboratory
- JSC - Johnson Space Center
- K - Kelvin temperature
- kg/yr - Kilograms per year
- KPLO - Korean Pathfinder Lunar Orbiter
- KREEP - Potassium (K), Rare Earth Elements, Phosphorous
- KSC - Kennedy Space Center
- KWe - Kilowatt electric
- LADI - Lunar Auger Dryer ISRU
- LCROSS - Lunar Crater Observation and Sensing Satellite
- LIDAR - Light Detection and Ranging
- LIRA - Lunar In-situ Resource Analysis
- LightWAVE - Light Water Analysis and Volatile Extraction
- LP3 - Lunar Propellant Production Plant
- LuSTR - Lunar Surface Technology Research
- LSII - Lunar Surface Innovation Initiative
- Lunar WETS - Lunar Water Extraction Techniques and Systems
- m - Meter
- Mat’l - Material
- min. - Minimum
- MMOST - Moon to Mars Oxygen and Steel Technology
- MRE - Molten Regolith Electrolysis
- MSFC - Marshall Space Flight Center
- mT - Metric Tonne
- NASA - National Aeronautics and Space Administration
- NIAC - NASA Innovation Advanced Concepts
- nom. - Nominal
- NH3 - Molecular formula for ammonia
- NSTRF - NASA Space Technology Research Fellowship
- O2 - Molecular formula for oxygen
- O2/yr - oxygen per year
- OH - Molecular formula for hydroxyl
- PEM - Proton Exchange Membrane
- PILOT - Precursor ISRU Lunar Oxygen Testbed
- PRIME - Polar Resources Ice Mining Experiment
- PSR - Permanently Shadowed Region
- SAA - Space Act Agreement
- SBIR - Small Business Innovation Research
- SO2 - Molecular formula for sulfur dioxide
- SOE - Solid Oxide Electrolysis
- SMD - Science Mission Directorate
- SPLICE - Safe and Precision Landing – Integrated Capabilities Evolution
- STMD - Space Technology Mission Directorate
- SSERVI – Solar System Exploration Research Virtual Institute
- STTR - Small business Technology Transfer
- Th - Thorium
- TP - Tipping Point
- TRL - Technology Readiness Level
- TVac - Thermal vacuum
- U - Uranium
- VIPER - Volatiles Investigating Polar Exploration Rover
- VSAT - Vertical Solar Array Technology
- wt% - Weigh percent

STMD Strategic Framework

- **The Vision:** The end goal is Strategic Framework. a single integrated environment that "ties everything together".
  - Thrusts are broad categories of strategic impact (Go, Land, Live, Explore)
  - Strategic Outcomes are high-level, measurable goals under each Thrust, and articulate primary areas of emphasis
  - Capability Areas provide the ability to conduct activities or meet objectives within acceptable constraints
    - They are organized by Thrust and the scope is documented using the OCT taxonomy
  - Technology Gaps are designated "context" by linking a taxonomy area to a Strategic Outcome
  - Descriptions/Figures of Merit (metrics) are created to inform details about the gap and how that gap may be closed

- **Current Status**
  - Completed: Thrusts, Strategic Outcomes, Capability Areas, and Technology Gaps
  - Envisioned Future Priorities created and approved to define STMD level priorities, plans, and budgets
  - Recent/on-going technology projects with metrics are being linked to Gaps and Outcomes via flexible STARPort software



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

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

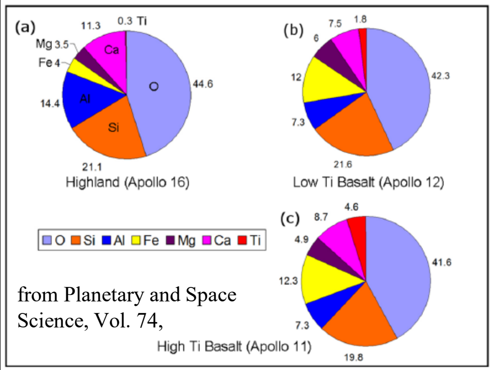
Autonomous Excavation, Construction, & Outfitting
Receive/remove regolith; provide resource information and manufacturing/construction commodities; common technologies

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

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

Lunar Resources for Commercial and Strategic Interests

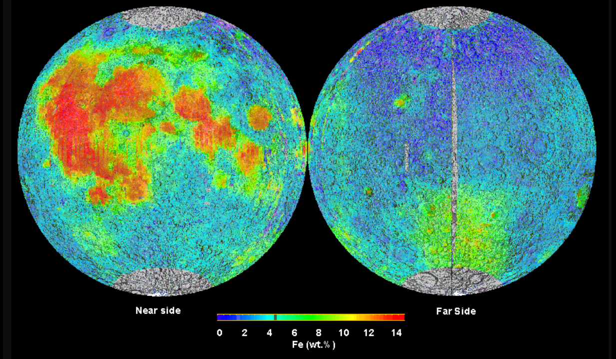
Elements in Lunar Regolith



from Planetary and Space Science, Vol. 74,

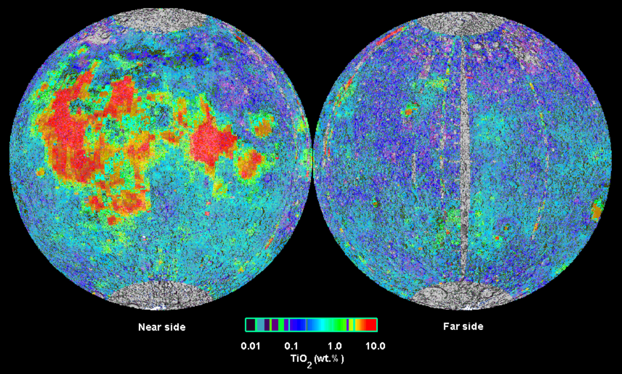
Clementine Iron Map of the Moon

Equal Area Projection



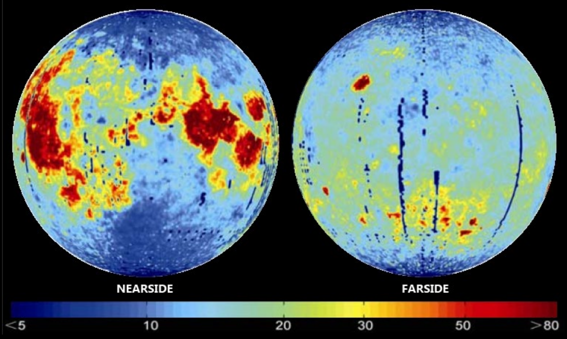
Clementine Titanium Map of the Moon

Equal Area Projection

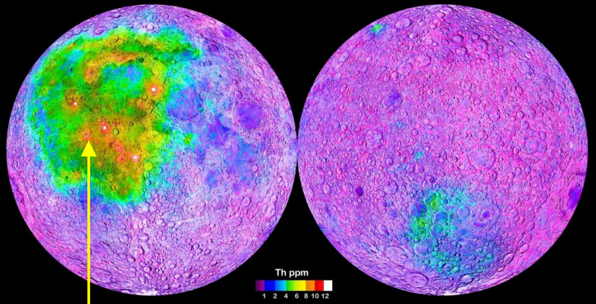


Estimated concentration of 3He

(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)

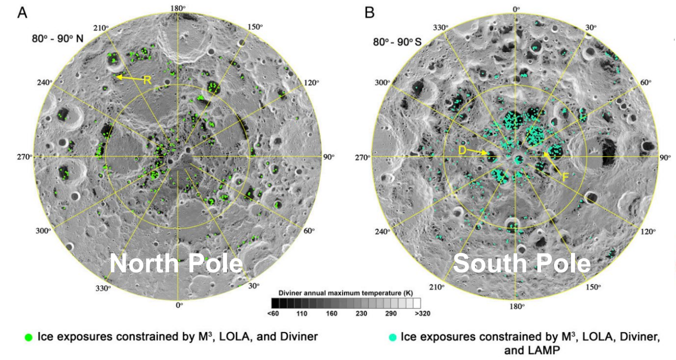
Prettyman et al., 2006;

Rare Earth Elements

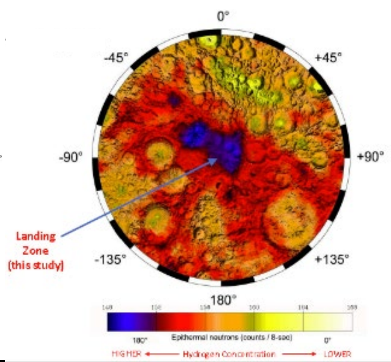
		Lunar Basalt	Lunar Breccias	Lunar Soil	Earth Crust
Pr	ppm	13	---	7	9.2
Nd	ppm	63	40	39	41.5
Sm	ppm	21	14	13	7.05
Eu	ppm	2.2	1.9	1.7	2
Gd	ppm	27	20	15	6.2

Evidence of Water & Volatiles at the Lunar Poles

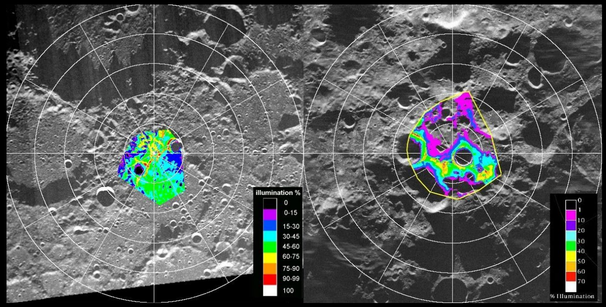
Spectral Evidence (Li, et. al)



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

In Situ Propellant & Consumable Production

Phases of Evolution and Use – *Need to Plan for Scale-up from the Start*

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"

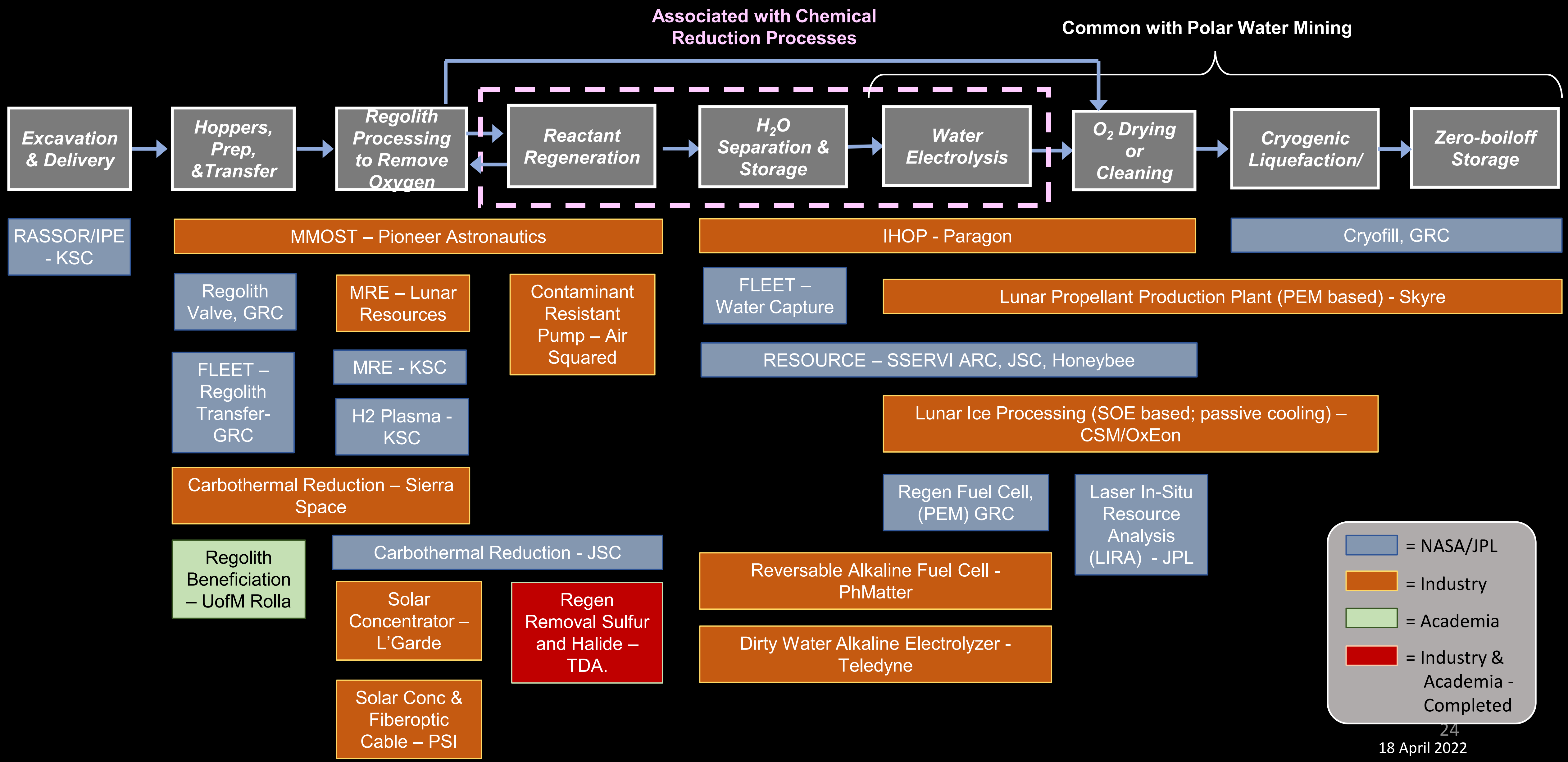
[4] Estimate from "Commercial Lunar Propellant Architecture" study

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

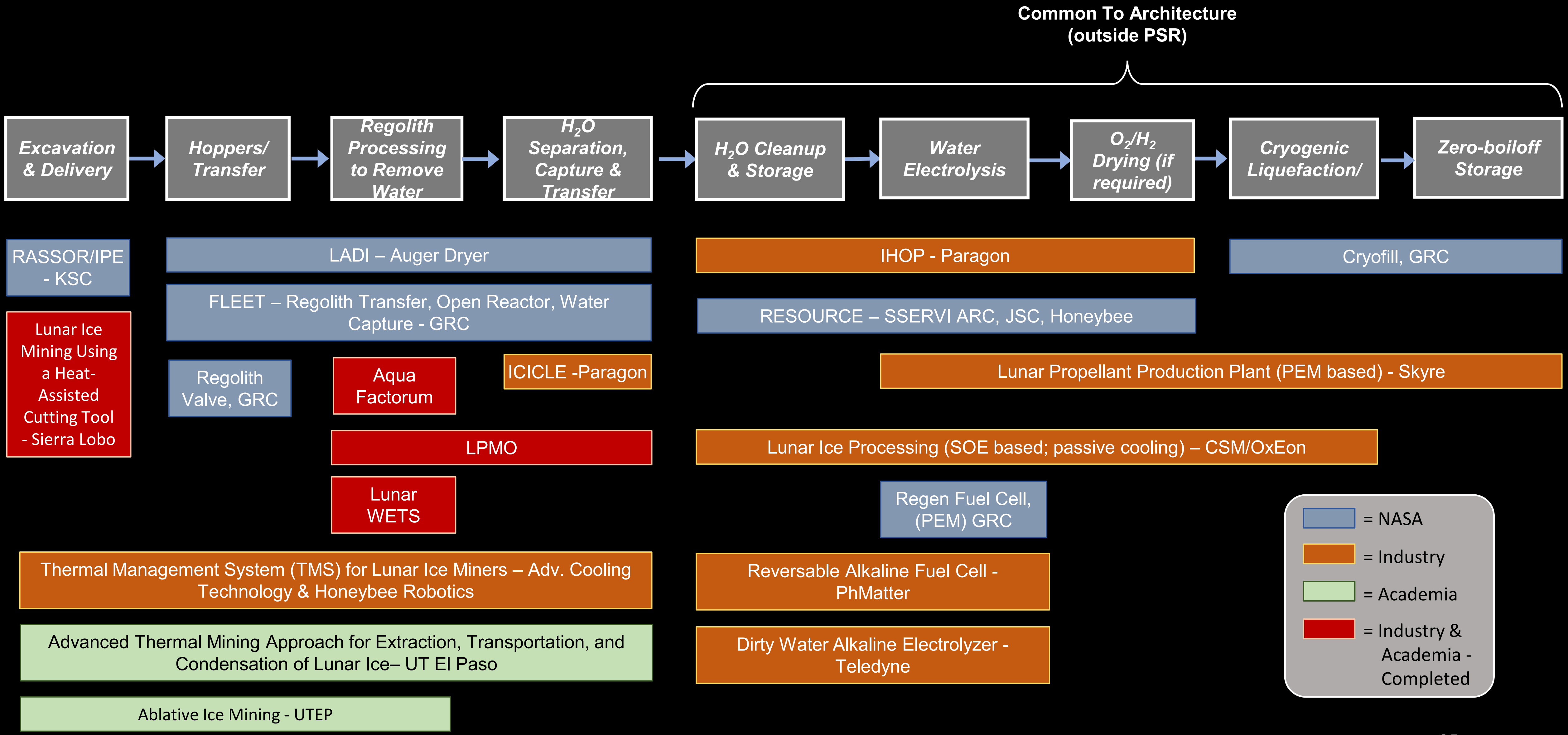
[6] APL Lunar Surface Innovation Consortium Suppy-Demand Workshop, 9/17/2020

- 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
- Table created before selection of SpaceX Starship for HLS. More rapid evolution to larger scale production may be warranted

Technology Projects for Oxygen Extraction ISRU Pilot Plant



Technology Projects for Water Ice ISRU Pilot Plant

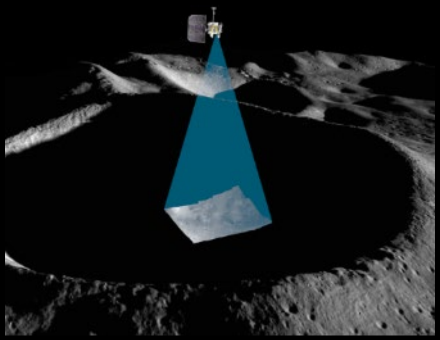


NASA Lunar Polar Science & Resource Assessment Missions – Current & In Development

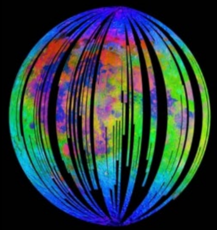
Orbital Missions

Lunar Reconnaissance Orbiter

ShadowCam on Korean Pathfinder Lunar Orbiter



Lunar Trailblazer

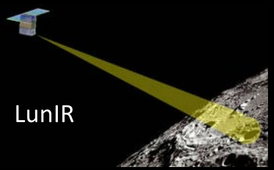


Artemis I Cubesats

Lunar IceCube

Lunar Flashlight

LunIR



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

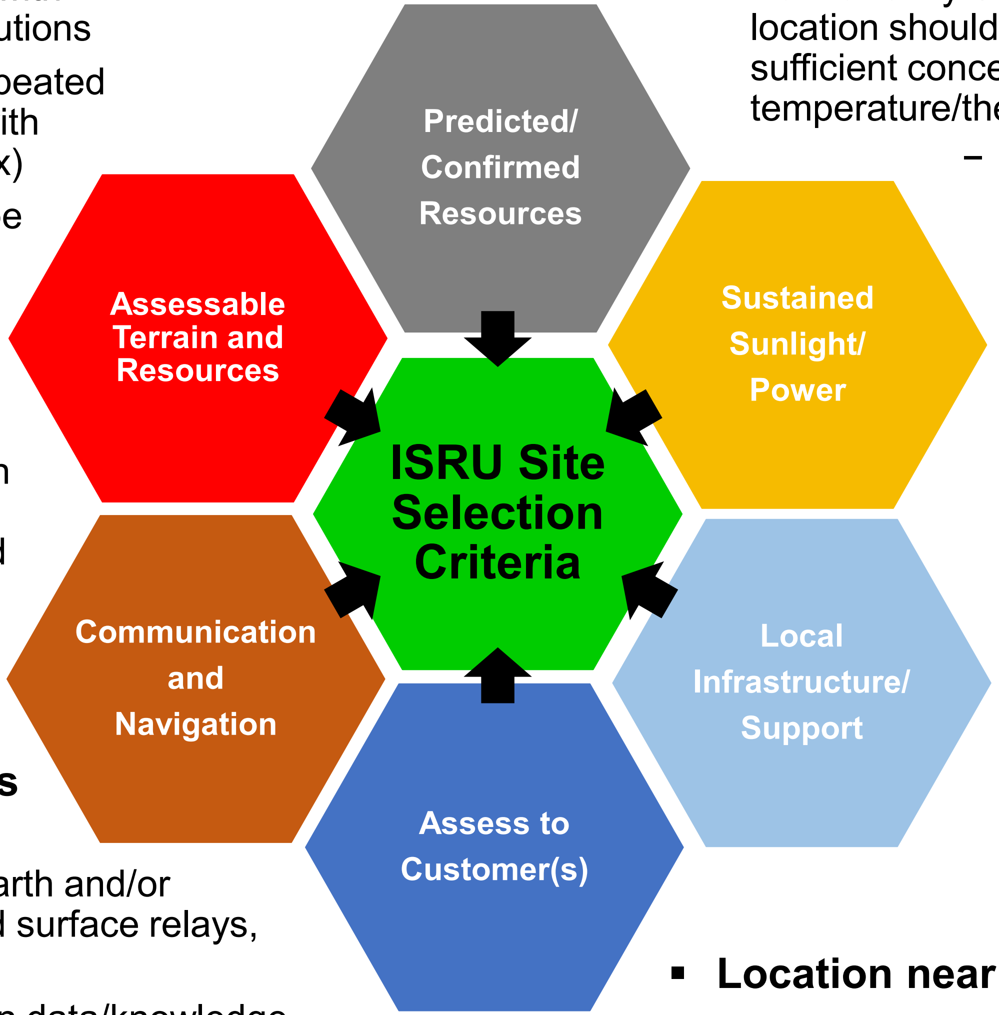
VIPER

- **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

Lunar Polar Ice Mining and Processing Site Location Criteria

- **Assessable Terrain & Resources**
  - Mining location relatively flat with minimal boulders/rock distributions
  - Location needs to support repeated ingress/egress of PSR/ISR with slopes <15 deg. (20 deg. max)
  - Resource location needs to be within 5 km (TBR) of water processing & commodity storage plant location
  - Traverse paths that have <15 deg slopes with minimal rocks, and no gullies between processing and customer (may require 'road'/ stabilized path after repeated usage)

- **Sustained Communications and Navigation**
  - Direct communication with Earth and/or Communication satellites and surface relays, esp. into PSR/ISR locations
  - High resolution surface terrain data/knowledge
  - Local navigation aids for mine site extraction operations and frequent/repetitive traverses



- **Predicted/Confirmed Resources**
  - Permanently Shadowed Region (PSR)/Ice Stable Region (ISR) location should have indications of water/ice volatile resources of sufficient concentration (>2 wt% water in top 1 m) including neutron, temperature/thermal, & spectroscopic data)
    - Prediction of ice depth with an anticipated lateral distribution sufficient to meet ISRU tonnage requirements to support multiple years of resource extraction (100's mt of product/yr possible)

- **Sustained Sunlight Near Resources:**
  - Sustained sunlight (>220 days with long periods of continuous sun)
  - Power in or directed into shadowed resource location (<5 km desired)
  - Processing Plant: Water Processing-H_2/O_2 Liquefaction and Storage within 1 km (TBR) of power generation/storage
  - Mine site in PSR: Excavation & Regolith Processing to Extract Water within 3.5 km (TBR) of power generation/storage

- **Location near Sustained Human Outpost/Customers**
  - Infrastructure support and Outpost/Landing pads within 5 km (TBR)
  - Crew/robotics for offloading, setup, & periodic maintenance