# Aspects of ISRU on the Moon
# NASA Perspective I

**National Academies of Sciences, Engineering, Medicine**

**Decadal Survey on Planetary Science and Astrobiology:**
**Panel on Mercury and the Moon**

Aug. 6, 2021

**Gerald (Jerry) Sanders/ISRU System Capability Lead**

# What is ISRU and the Challenges

# ARTEMIS: Humanity's Next Giant Leap

**Moon to Mars**

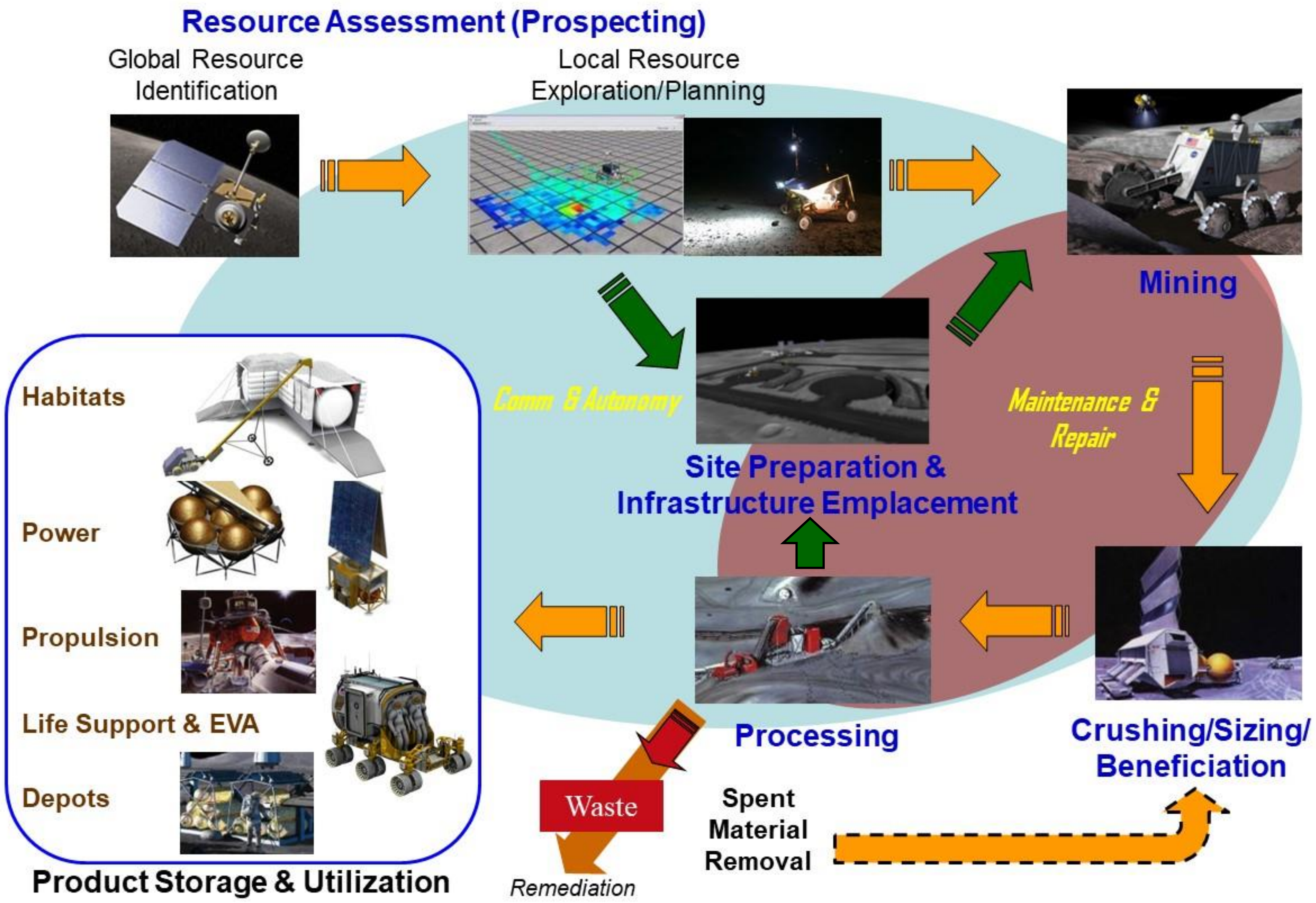
- Returning Americans to the Moon: 1st Woman & 1st Person of Color
- Learning to live and work on the Moon
- Translating lessons learned so that the United States has capabilities and operational experience for a mission to Mars
- Inspires the next generation of explorers, researchers, scientists, and engineers worldwide

"The United States will lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the **United States will lead the return of humans to the Moon** for long-term exploration and utilization, **followed by human missions to Mars** and other destinations"

**Space Policy Directive One**

# What Is In Situ Resource Utilization (ISRU)?
## *Prospect to Product*

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



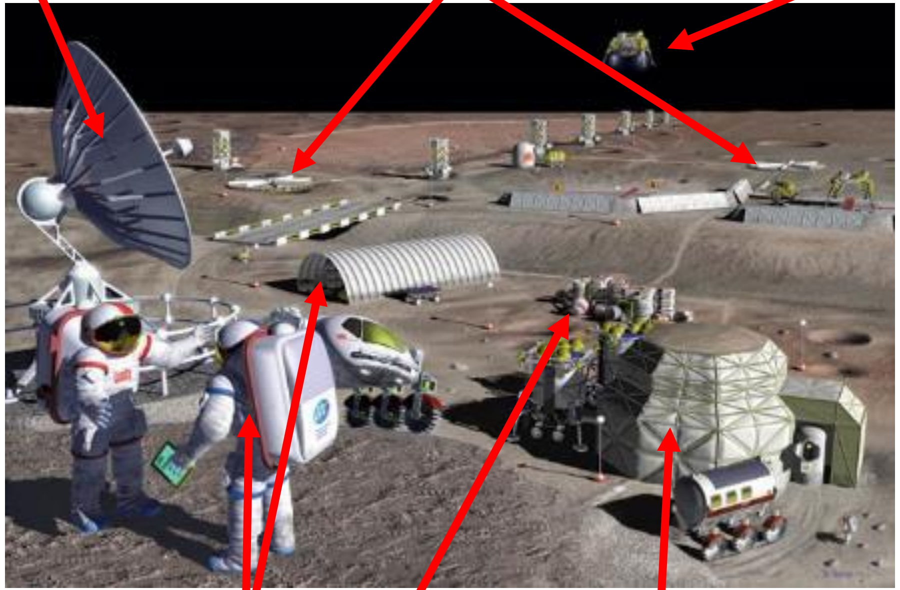

- **‘ISRU’ is a capability involving multiple elements** (mobility, product storage and delivery, power, crew and/or robotic maintenance, etc.) **to achieve final products**
- **‘ISRU’ does not exist on its own.** By definition, it must connect and tie to users/customers of ISRU products and services.
- **Lunar ISRU Purpose**
  - Sustain and Grow Human Lunar Surface Exploration
  - Reduce the Risk and Prepare for Human Mars Exploration
  - Expand Terrestrial & Enable Economic Expansion into Space

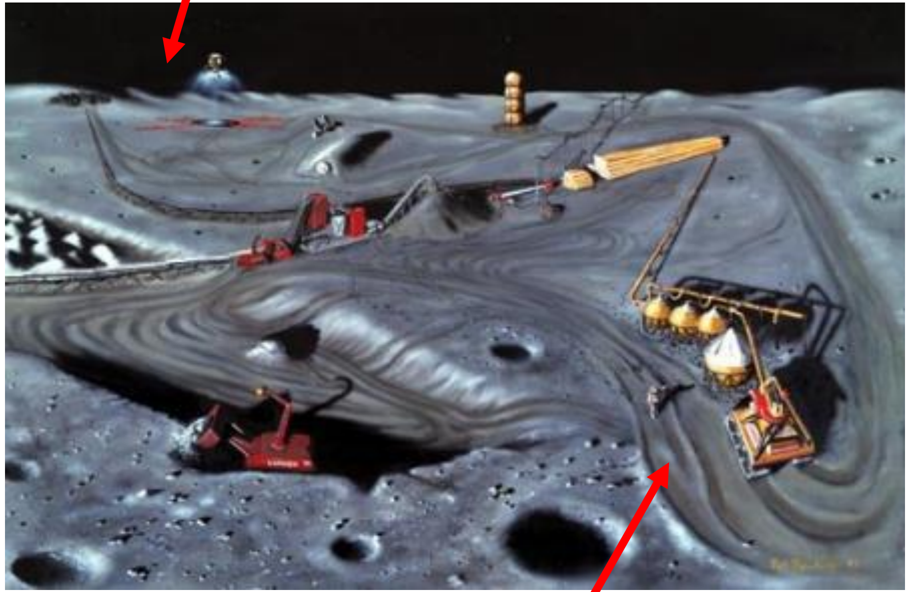
# ISRU Must Operate as Part of A Larger Architecture

**Communications**
- To/From Site
- Local

**Power**:
- Generation
- Storage
- Distribution

**Transportation** to/from Site:
- Navigation Aids
- Loading & Off-loading Aids
- Fuel & Support Services

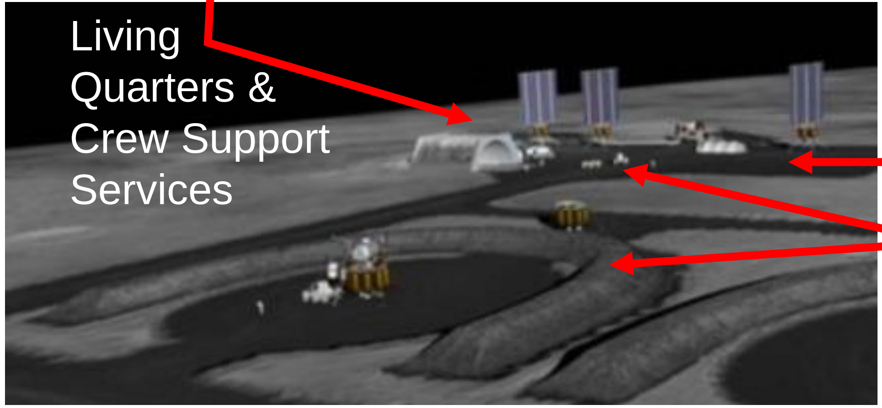




**Coordinated Mining Ops:**
Areas for:
i) Excavation
ii) Processing
iii) Tailings

**Maintenance & Repair**

**Logistics Management**



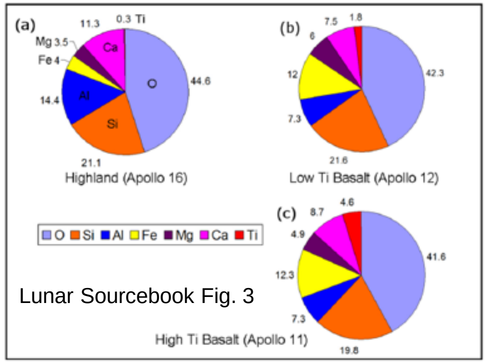
Living Quarters & Crew Support Services

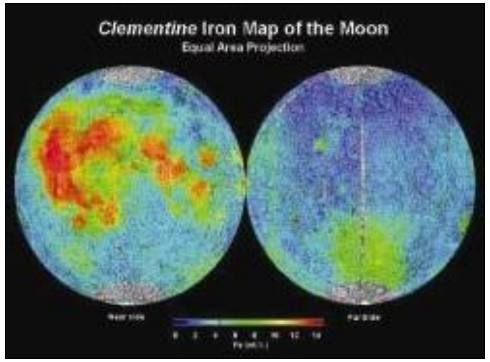
**Roads**

**Construction and Emplacement**

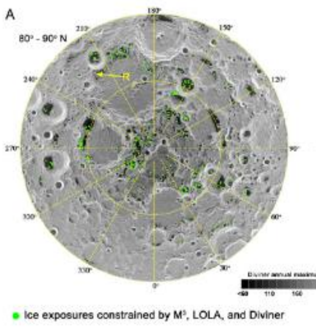
# Lunar Resources

## Regolith, Solar Wind Volatiles, Polar Water/Volatiles

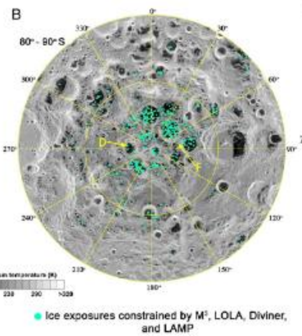


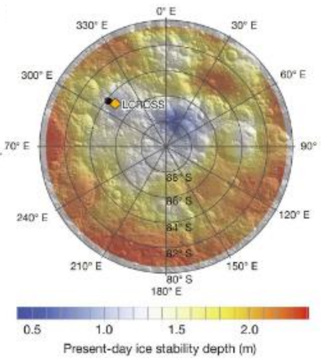

North Pole



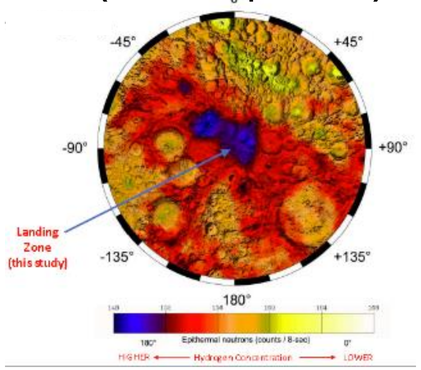

South Pole




Ice Stability Temperatures




Evidence of Hydrogen (Lunar Prospector NS)




## Lunar Regolith

- **>40% Oxygen by mass**; numerous metals (Fe, Al, Ti)
  - Silicate minerals make up over 90% of the Moon
- Mare – Basalt
  - 15-20% Plagioclase, 15-24% Pyroxene, 3-4% Olivine, 2-10% Ilmenite, 45-53% Agglutinate glass
- **Highland/Polar area**
  - >75% Anorthite, Pyroxene, 7% Olivine
- Pyroclastic Glass
- KREEP (Potassium, Rare Earth Elements, Phosphorous)
- Solar Wind Implanted Volatiles

Fegley and Swindle 1993

| Volatile | Concentration ppm (μg/g) | Average mass per $m^3$ of regolith (g) |
|---|---|---|
| H | 46 ± 16 | 76 |
| $^3$He | 0.0042 ± 0.0034 | 0.007 |
| $^4$He | 14.0 ± 11.3 | 23 |
| C | 124 ± 45 | 206 |
| N | 81 ± 37 | 135 |
| F | 70 ± 47 | 116 |
| Cl | 30 ± 20 | 50 |

## Polar Water/Volatiles

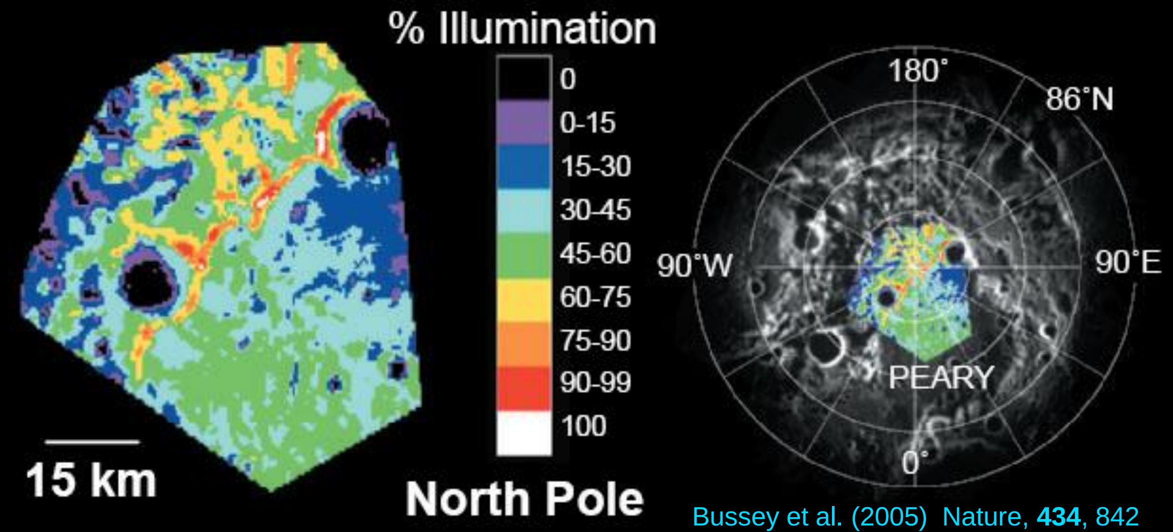
- LCROSS impact estimated **5.5 wt%** water along with other volatiles
- Green and blue dots show positive results for surface water ice and temperatures <110 K using orbital data.
- Spectral modeling shows that some ice-bearing pixels may contain **~30 wt % ice** (mixed with dry regolith)

➢ *Without direct measurements, form, concentration, and distribution of water is unknown*

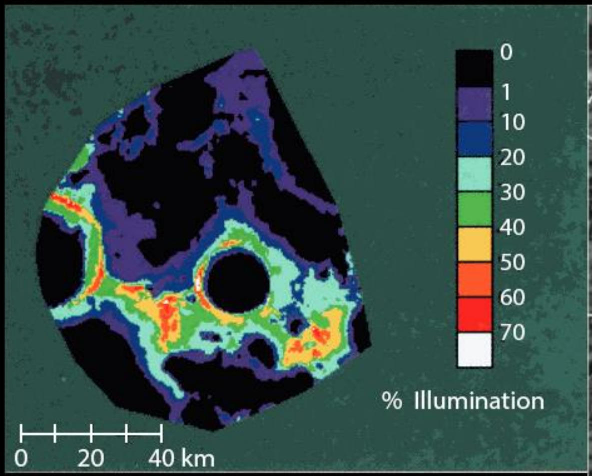
| | Concentration (%wt)* |
|---|---|
| $H_2O$ | 5.5 |
| CO | 0.70 |
| $H_2$ | 1.40 |
| $H_2S$ | 1.74 |
| Ca | 0.20 |
| Hg | 0.24 |
| $NH_3$ | 0.31 |
| Mg | 0.40 |
| $SO_2$ | 0.64 |
| $C_2H_4$ | 0.27 |
| $CO_2$ | 0.32 |
| $CH_3OH$ | 0.15 |
| $CH_4$ | 0.03 |
| OH | 0.00 |
| $H_2O$ (adsorb) | 0.001-0.002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

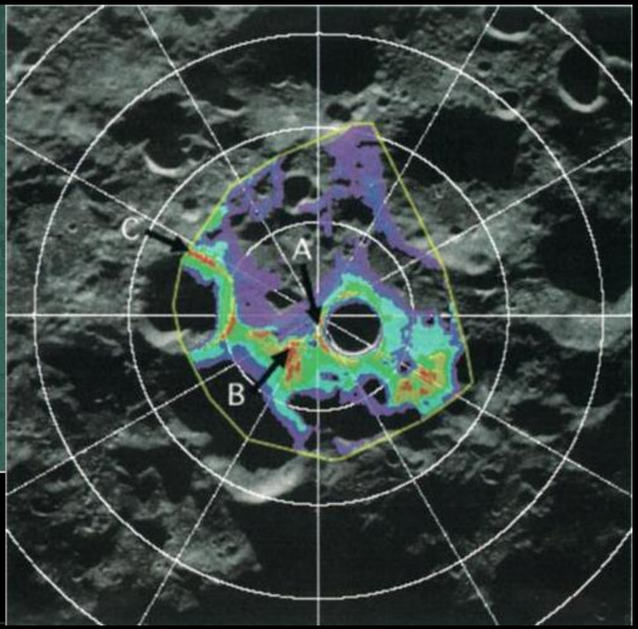
# NASA Artemis is Focused on the Lunar South Pole

**“Peaks of Eternal Light” and “Permanently Shadowed Regions” exist on the lunar poles**


Bussey et al. (2005) Nature, **434**, 842




South Pole Illumination

Bussey et al. (1999) GRL, 26, 1187-1190

# ISRU Development and Implementation Challenges

## Space Resource Challenges 1

**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 2

**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 3

**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 4

**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?**

# Top 3 ISRU Development and Mission Insertion Challenges

- **Resource Uncertainty and Impact on ISRU Development & Implementation (R1, R2)**
  - Limited information (LCROSS) on actual lunar water/volatile characteristics requires development of several options in parallel or significant delays in polar ice mining will occur
  - Current science missions, including VIPER, will help with understanding polar water/volatiles, but more is required to determine if the water resources are economically minable ‘reserves’

- **Achieving Long Duration, Autonomous Operation in Mission Environments (O1, O3, T2)**
  - Current SOA technologies and systems for ISRU are not adequate;  limited testing and scale of processing to date
  - ISRU requires long duration operations (years) which makes Earth-based development and certification testing under mission environments with adequate simulants difficult and expensive
  - Surviving and operating in permanently shadowed polar regions while interacting with abrasive regolith is critical for polar water prospecting and mining

- **Insertion into Lunar and Mars Human Mission Architectures (I1)**
  - Transportation and lander elements need to be designed from the start with ISRU propellants and surface refueling in mind.
  - Transition strategy from Earth-supplied propellants/depots to Lunar-supplied propellants required
  - Mars human architectures are extremely risk averse to incorporating Mars water resources into the architecture, even with lunar ISRU efforts applicable to Mars

# 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
  - Vacuum operation and exposure: electronics/power systems, reactor pressures/leakage, cold welding, etc.

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

# 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 Highland 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)<br>M = Medium Impact - Important for longer-term sustained operations or for non-polar regions<br>L = Low Impact - Limited importance to area of ISRU; limited impact to the architecture | **ISRU Operations**<br>- Definition: The SKG is applicable to all ISRU areas as well as potentially other surface activities., e.g. communication and navigation<br>- 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

# Lunar ISRU Development And Demonstration Plans

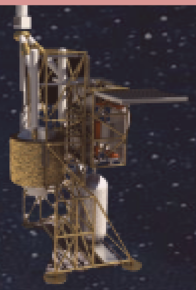
# NASA Space Technology Mission Directorate (STMD) Strategic Framework

| Lead | Thrusts | Outcomes | Primary Capabilities |
|---|---|---|---|
| **Ensuring American global leadership in Space Technology**<br>• Lunar Exploration building to Mars and new discoveries at extreme locations<br>• Robust national space technology engine to meet national needs<br>• U.S. economic growth for space industry<br>• Expanded commercial enterprise in space | **Go**<br>Rapid, Safe, and Efficient Space Transportation | • Develop nuclear technologies enabling fast in-space transits.<br>• Develop cryogenic storage, transport, and fluid management technologies for surface and in-space applications.<br>• Develop advanced propulsion technologies that enable future science/exploration missions. | • Nuclear Systems<br>• Cryogenic Fluid Management<br>• Advanced Propulsion |
| | **Land**<br>Expanded Access to Diverse Surface Destinations | • Enable Lunar/Mars global access with ~20t payloads to support human missions.<br>• Enable science missions entering/transiting planetary atmospheres and landing on planetary bodies.<br>• Develop technologies to land payloads within 50 meters accuracy and avoid landing hazards. | • Entry, Descent, Landing, & Precision Landing |
| | **Live**<br>Sustainable Living and Working Farther from Earth | • Develop exploration technologies and enable a vibrant space economy with supporting utilities and commodities<br>  • Sustainable power sources and other surface utilities to enable continuous lunar and Mars surface operations.<br>  • Scalable ISRU production/utilization capabilities including sustainable commodities on the lunar & Mars surface.<br>  • Technologies that enable surviving the extreme lunar and Mars environments.<br>  • Autonomous excavation, construction & outfitting capabilities targeting landing pads/structures/habitable buildings utilizing in situ resources.<br>• Enable long duration human exploration missions with Advanced Life Support & Human Performance technologies. | • Advanced Power<br>• In-Situ Resource Utilization<br>• Advanced Thermal<br>• Advanced Materials, Structures, & Construction<br>• Advanced Life Support & Human Performance |
| | **Explore**<br>Transformative Missions and Discoveries | • Develop next generation high performance computing, communications, and navigation.<br>• Develop advanced robotics and spacecraft autonomy technologies to enable and augment science/exploration missions.<br>• Develop technologies supporting emerging space industries including: Satellite Servicing & Assembly, In Space/Surface Manufacturing, and Small Spacecraft technologies.<br>• Develop vehicle platform technologies supporting new discoveries.<br>• Develop transformative technologies that enable future NASA or commercial missions and discoveries | • Advanced Avionics Systems<br>• Advanced Communications & Navigation<br>• Advanced Robotics<br>• Autonomous Systems<br>• Satellite Servicing & Assembly<br>• Advanced Manufacturing<br>• Small Spacecraft<br>• Rendezvous, Proximity Operations & Capture |

# Lunar Surface Innovation Initiative (LSII) Overview

## In-Situ Resource Utilization

Collection, processing, storing and use of material found or manufactured on other astronomical objects.
- Sub-scale ice mining and O2 extraction demonstrations targeted for mid-2020's
- ISRU Pilot Plant demonstration by late 2020's



## Surface Excavation & Construction

Enable affordable, autonomous manufacturing or construction.
- Targeting a Small Pilot Lunar Surface Excavation demonstration in mid-2020's
- Scaled Construction demonstrations in mid- and late-2020's

## Sustainable Power

Enable continuous power throughout lunar day and night.
- Regenerative Fuel Cell (RFC), Wireless Charging, Chemical Heat Integrated Power Source (CHIPS), and Lunar Surface Solar Arrays demonstrations in mid-202's
- Targeting Fission Surface Power demonstration in late 2020's

## Lunar Dust Mitigation

Mitigate lunar dust hazards.
- Targeting multiple Lunar Dust Mitigation demonstrations (component and subsystem-level) starting in early 2020's

## Extreme Access

Access, navigate, and explore surface/subsurface areas.
- Subsystem and component-level demonstrations throughout the 2020's, including the Cooperative Autonomous Distributed Robotic Explorer (CADRE) in 2023

## Extreme Environments

Enable systems to operate through out the full range of lunar surface conditions.
- Targeting demonstrations on Lunar Night and Material Survivability, Lunar Exposure Platform (Lunar MISSE), Planet & Lunar Environment Thermal Toolbox Elements (PALETTE), COLDArm, starting in early 2020's

# Strategy For ISRU Insertion into Human Exploration

## Maximize Ground Development – Use Flight for Critical Information and Eliminate Risk

- **Know Customer Needs and Gaps**
  - Work with Artemis elements, Moon/Mars Surface Architecture, and International Partners
  - Work with Industry/Academia: Lunar Surface Innovation Consortium
- **Perform Ground Develop of Hardware and Systems until Flight**
  - Initiate a full range of ISRU & other discipline technologies across all TRLs (Technology Pipeline) to enable ISRU capabilities
  - Develop lunar ISRU components and subsystems with a Mars-forward application
  - ➢ **Engage Industry, Academia, and the Public** to lay the foundation for long-term lunar economic development
- **Reduce Risk of including ISRU into Human Lunar Exploration By Utilizing CLPS Missions**
  - Understand lunar polar resources for technology development, site selection, mission planning
  - Obtain critical data (ex. regolith properties, validate feasibility of ISRU process)
  - Demonstrate proof-of-concept and reduce risk
  - Demonstrate critical ISRU hardware and validate Pilot/Full scale designs
- **Perform End-to-End ISRU Production Pilot Mission** at sufficient scale to eliminate risk of Full-scale system
- **Demonstrate use of ISRU Derived Products:** Ascent vehicle, hopper, fuel cell, crew $O_2$, …

➢ **ISRU must first be demonstrated on the Moon before it can be mission-critical**

- 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.

# Lunar ISRU Mission Consumables:
## Polar Water and Oxygen from Regolith

- **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 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

➢ **Current Plan:** <u>Lead with Water Mining</u>/Follow with $O_2$ from Regolith Dual Path
  - Perform PRIME-1 CLPS and VIPER to begin to understand lunar polar water availability
  - Develop $O_2$ from Regolith high-fidelity ground demo in a TVC in parallel
  - Utilize results from these activities to inform the 2-3 subsystem tech demos in the 2024-2026 timeframe which will culminate in the scalable pilot.

# Key Questions to Address to Determine Path

**What do we need to demonstrate to relevant scale ISRU on the Lunar surface?**

## Polar Water Mining Path

- **Are there sufficient quantities and concentrations of accessible ice** to produce desired amounts of $O_2$ and $H_2$?
  - Access PSRs or other locations with potential ice deposits
  - Access sub-surface icy regolith
  - Assess ice concentration at multiple sites to estimate quantity
- **Can lunar ice be extracted** and converted into $O_2$ and $H_2$?
  - Excavate icy regolith
  - Extract water from icy regolith
  - Assess purity and contaminates in water
  - Electrolyze water to produce $O_2$ and $H_2$

## Oxygen from Regolith Path

- **Can clean $O_2$ be produced from regolith** found near the lunar poles?
  - Excavate granular material
  - Process regolith/benefaction
  - Extract Oxygen
  - Purify product

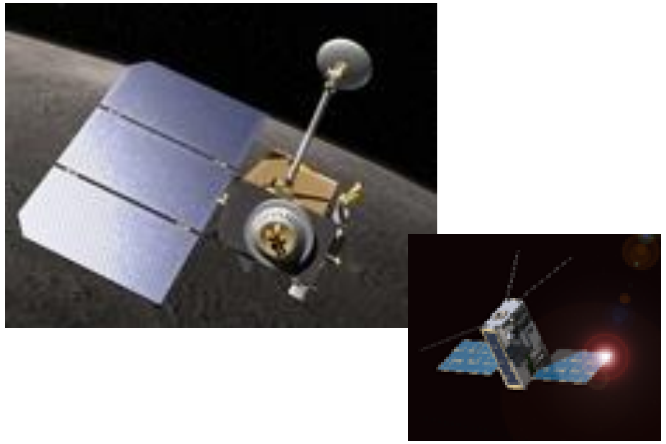
## Pilot Plant

- **Can sufficient quantities propellant be produced stored**?
  - Produce propellant at a rate of 100's to 1000's of kg per year
  - Liquefy all products
  - Store products for >1 year
- **Can the system survive the environment?**
  - Operate without crew intervention for 1-5 years
  - Survive eclipse periods
  - Operate with abrasive regolith
  - Operate in permanently shadowed region temperature environment (40 to 100 K)

# Resource Assessment for ISRU

### Remote Assessment

Orbiters, CubeSats



<u>Goals</u>:

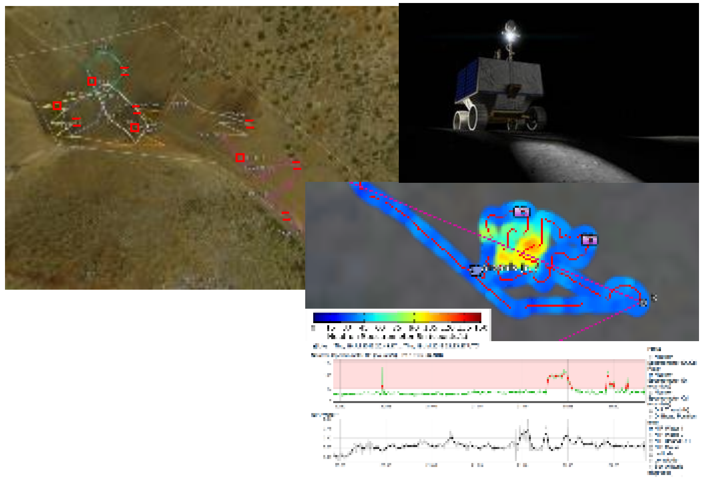
i. Obtain data on terrain, minerals, and water resources to select landing sites of consideration
ii. Obtain data at resolution to plan surface Exploratory Assessment of terrain and resources

<u>Instruments</u>

- Better mineral resolution for chemistry and hydration
- Passive and active subsurface hydrogen and layer

### Exploratory Assessment

Rovers, Hoppers, Aerial Vehicles, Impactors, Instrumented Landers



<u>Goals</u>:

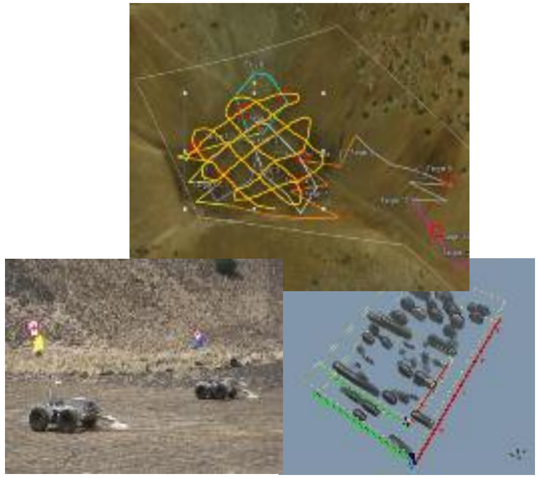
i. Obtain data on physical/mineral characteristics and water/volatiles.
ii. Obtain sufficient data to determine if the site warrants a Focused Assessment of resources

<u>Instruments</u>

- Should cover physical/geotech, chemical/mineral, and volatile characterization
- Passive and active subsurface assess

### Focused Assessment, Mapping, & Planning

Rover or Crew



<u>Goals</u>:

i. Ensure sufficient resources exist in form and location expected
ii. Build 3-D interpretation of data to define resource for mining operations

<u>Instruments</u>

- Should cover physical, chemical/mineral, and volatile characterization
- Passive and active subsurface assess

**Resource Assessment is Need for Artemis Base Camp site selection and long-term ISRU Commercialization**

# Polar Ice Resource Assessment – Current Development

- **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
  - ColdARM – JPL - GCD
  - Trident Auger – Honeybee Robotics - VIPER
  - WRANGL3R - Water Regolith ANalysis for Grounded Lunar 3d Reconnaissance - Univ of Texas El Paso - LuSTR
- **Instruments for Physical/Geotechnical Characterization**
  - Material Characterization while Drilling on Lunar/Martian Surface – ESI with CSM - Completed
  - High TRL Rover Lidar – NASA GSFC
  - Moon-Mars Ice Challenge – NASA LaRC
  - Percussive Hot Cone Penetrometer and GPR – Mich Tech - LuSTR
- **Instruments for Mineral 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
- **Mobility and Instruments for Resource Assessment**
  - L-Puffer/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

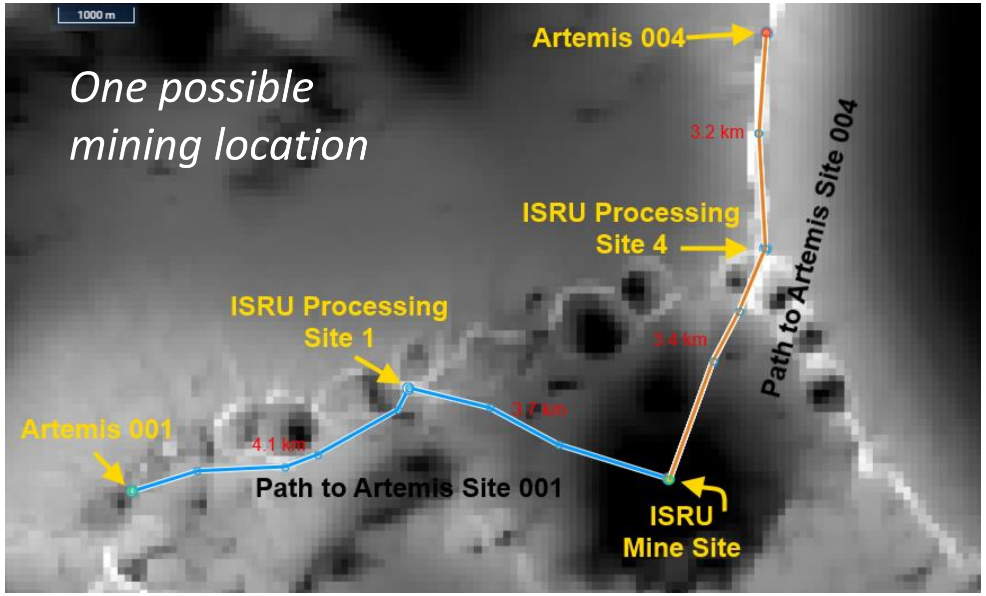
## Selected for CLPS
(by SMD and STMD)

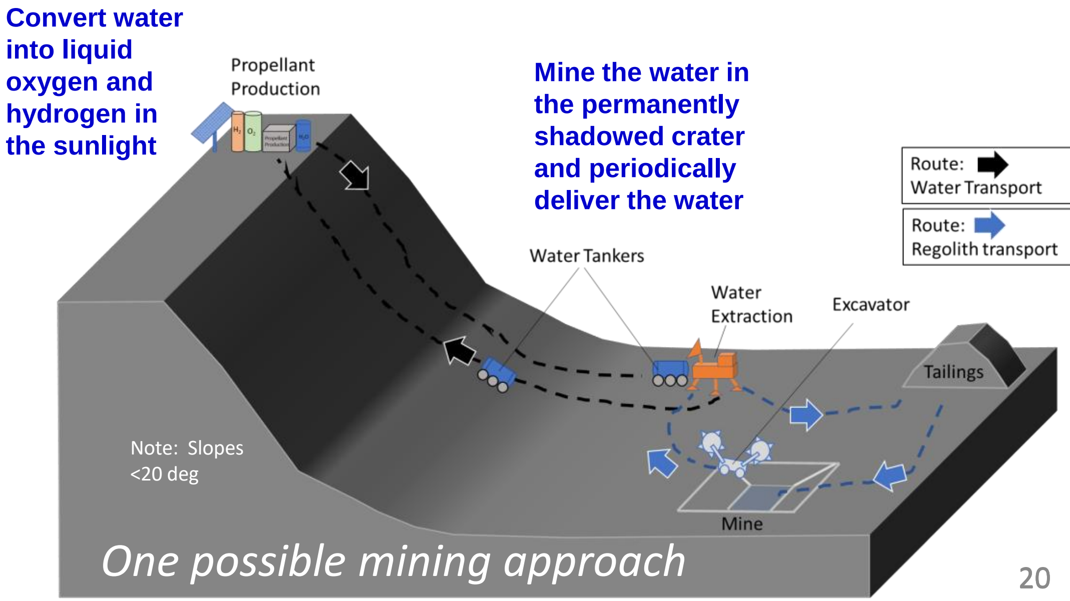
| Astrobotic 2021 | Masten 2022 (SP) | Firefly 2023 | IM Prime-1 2022 (SP) | Ast. VIPER 2023 (SP) | |
|---|---|---|---|---|---|
| | | | | | **Mineral Characterization** |
| X | X | | | X | NIRVSS - InfraRed Spec |
| | X | | | | L-CIRiS - Compact InfraRed Imaging System |
| | | | | | eXTraterrestrial 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 |
| | | | | | **Hydrogen Measurement** |
| | | | | | NSS - Neutron Spectrometer |
| | | | | | NMLS - Neutron Measurement at the Lunar Surface |
| X | X | | | X | NIRVSS -InfraRed Spec (surface and bound $H_2O$/OH) |
| | | | | | **Imager** |
| | X | | | | Heimdall - Digital Video Recorder/4 Cameras |
| | | | | | **Physical Properties/Acquisition** |
| | | X | | | LISTER - Heatflow Probe |
| | | 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** |
| | | | | | CubeRover (SBIR) |
| | X | | | | MoonRanger (LSIPT) |
| | | | | | L-PUFFER/CADRE (JPL) |
| | | | | | NeuRover (SBIR) |

# Polar Ice/Water Mining – Overview & 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 - Active
   - 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
2. **Subsurface Heating - Contained**
   - PVEx – Honeybee Robotics – SBIR Phase II – completed
   - Thermal Management for Lunar Ice Miners (w/ PVEx) - Advanced Cooling Technologies – SBIR Phase I/II - Active
3. **Subsurface Heating/Ablating and Volatile Release Capture**
   - Ablative Arc Mining for In-Situ Resource Utilization – UT El Paso - LuSTR – Active
   - Lunar Polar Propellant Mining Outpost – TransAstra – NIAC Phase II - Active
   - Lunar Water Extraction Techniques and Systems – TransAstra – SBIR Phase I – Active
   - Thermal Mining of Ices on Cold Solar System Bodies – CSM – NIAC Phase I - completed

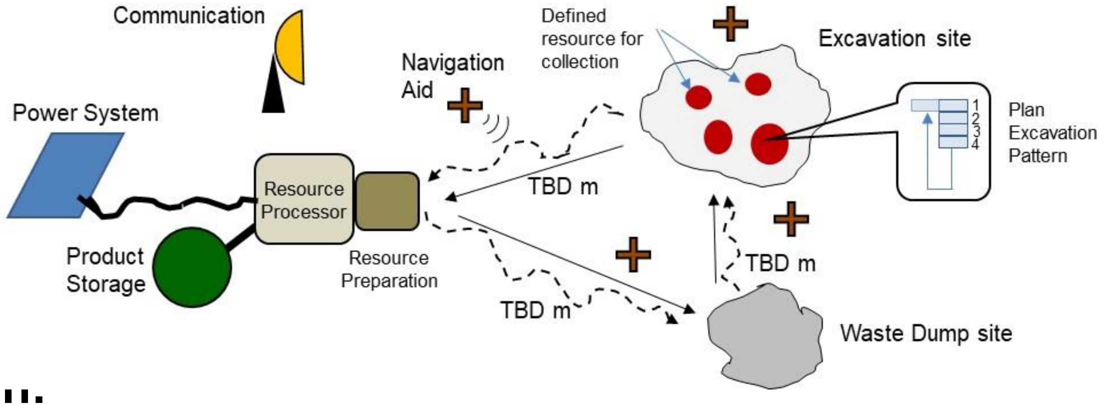


# Oxygen (Metal) from Regolith - Overview & Current Development

**Over 20 processes have been identified to extract oxygen from regolith**

- Components required range from TRL 3 to TRL 9
- Previously focused on Mare regolith;  now Highland
- Typically, as processing temps increase, $O_2$ yield increases, and technical and engineering challenges increase




**Oxygen Extraction Methods under development/consideratio…**

1. Carbothermal Reduction w/ Methane
   - Carbothermal Reduction Reactor Design – Sierra Nevada Corp (SNC) – 2 SBIR Phase IIIs, and COPR Tipping Point– Active
   - CaRD - Carbothermal Reduction Demonstration – GCD JSC - Active
2. Molten Regolith Electrolysis (MRE)
   - Molten Regolith Electrolysis - Lunar Resources – NASA SBIR Phase I/II and NSF SBIR Phase II – Active
   - Molten Regolith Electrolysis Tech Maturation – KSC – GCD and ECI – Active
3. Ionic Liquid Reduction and Electrolysis reactors for $O_2$/metals
   - RRILE – Resource Recovery with Ionic Liquid for Exploration - MSFC – GCD - Active
   - Ionic Liquid-Assisted Electrochemical Extraction of Oxygen - Faraday Technology - SBIR Phase I – Completed
4. Plasma Hydrogen Reduction
   - Plasma Hydrogen Process feasibility assessment – KSC – CIF – Active
   - Plasma Hydrogen Reactor design and control – KSC – GCD – FY22
5. Moon to Mars Oxygen and Steel Technology (CO/$H_2$ Reduction) - Pioneer Astronautics - SBIR Phase II Sequential - Active
6. Carbothermal/Vapor Pyrolysis with Solar Concentrator – Blueshift - SBIR Phase I - Completed

# Water Processing – Overview & Current Development

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

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

# ISRU Lunar Development and Demonstration Timeline

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

CLPS Drill Down Select

High-fidelity Simulant Production

Oxygen from Lunar Simulant Ground Demos

Polar Resources Ice Mining Experiment (Prime-1) on CLPS

Volatiles Investigation Polar Exploration Rover (VIPER)

ISRU Subsystem Consumables Extraction Demos

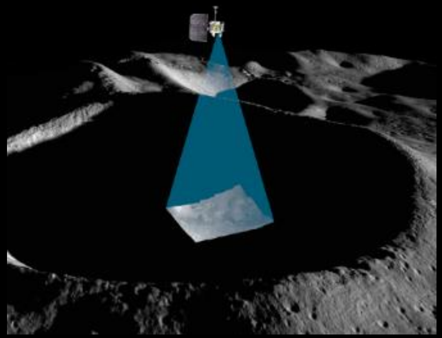
Scalable Pilot - ISRU Systems for Consumable Production

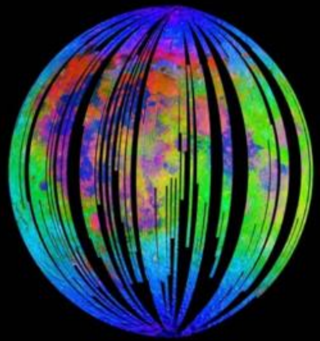
*2019* → *203x*

# Lunar Science & Resource Assessment

## Orbital Missions


Lunar Reconnaissance Orbiter


ShadowCam on Korean Pathfinder Lunar Orbiter


*Lunar Trailblazer*


Lunar IceCube

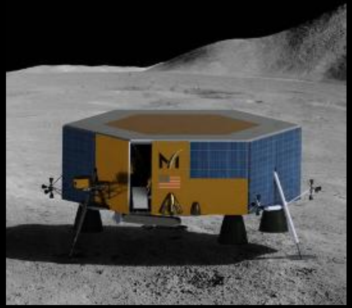

Lunar Flashlight


LunaH-Map

## Surface Missions


Astrobotics


Intuitive Machines


Masten


PRIME-1

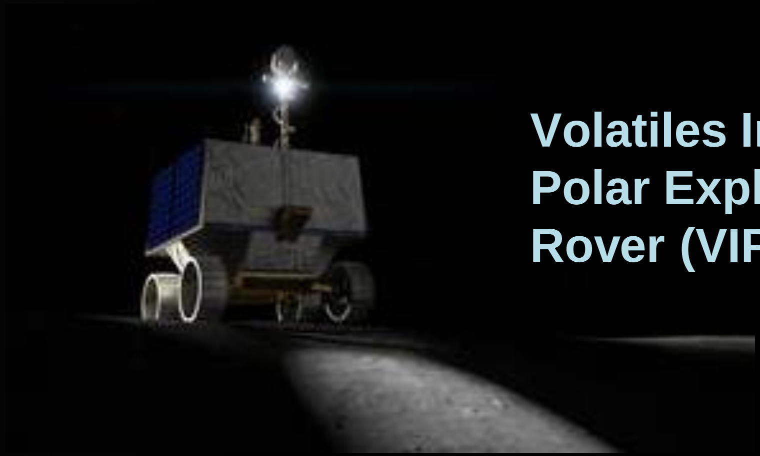

VIPER

# PRIME-1 & VIPER

## First Steps toward surface understanding of Polar Water and Volatiles

### Polar Resources Ice Mining Experiment (Prime-1) on CLPS

- 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)



### Volatiles Investigation Polar Exploration Rover (VIPER)

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

# In Situ Propellant & Consumable Production

## 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"

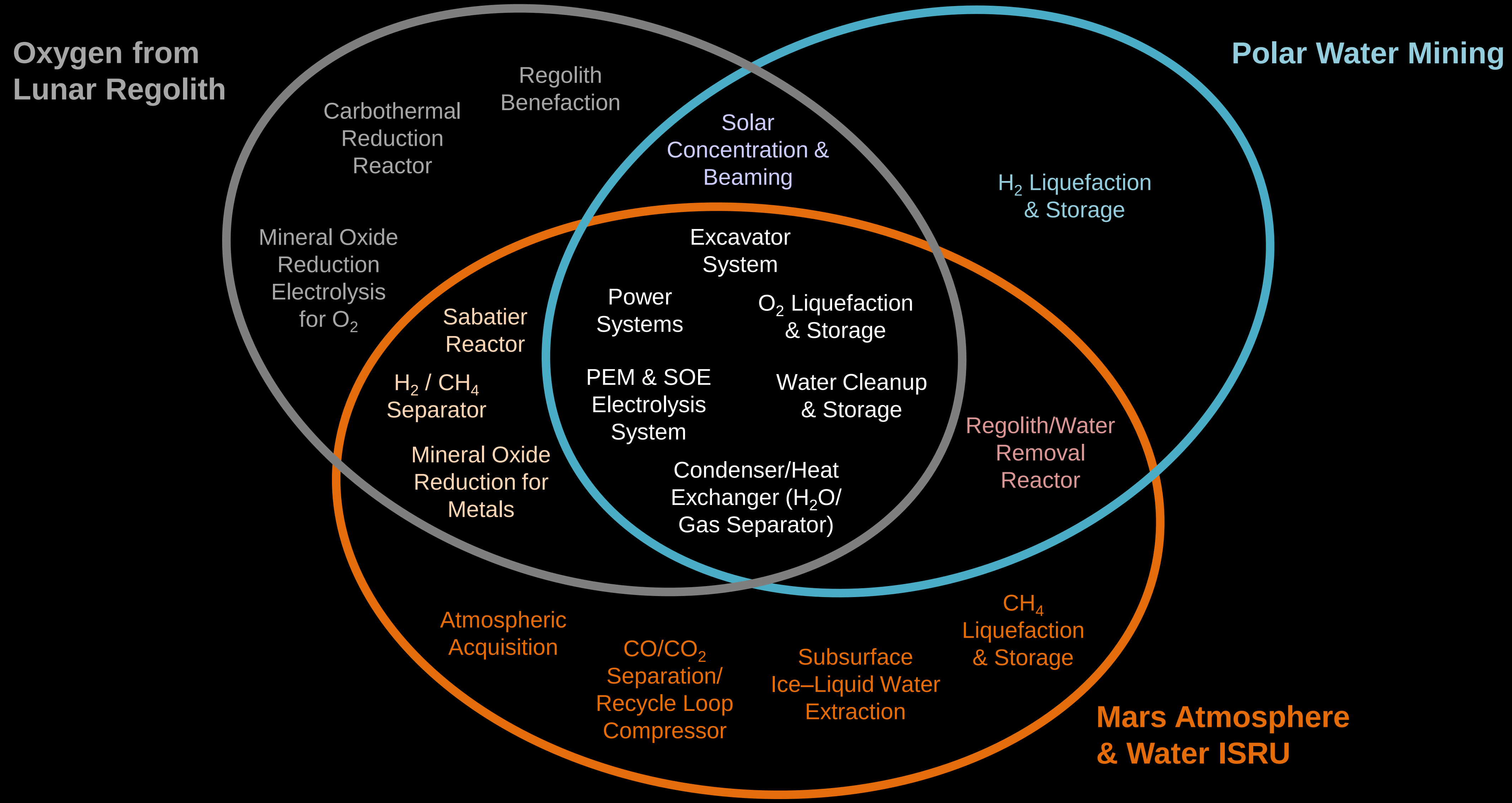
[4]Estimate from "Commercial Lunar Propellant Architecture" study

[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
- ➢ Significant Scale up will be required for long-term commercial operations

# ISRU Technology Synergy



# Lunar ISRU – Mars Forward

- **Multiple technologies and subsystems are in work and planned that are applicable to both Moon and Mars ISRU (as well as regenerative fuel cells and life support systems)**

- **Lunar ISRU operational experience and mission validations will reduce the risk and prepare for Human Mars Exploration**
  - Resource assessment and mapping
  - Robotic deployment of hardware and systems
  - Remote and autonomous operations
  - Product liquefaction, storage, transfer, and usage

- **With proper attention to production rates, modularization, and interfaces, almost the same subsystem modules and excavators can be utilized on both Moon and Mars missions**

**Lunar Production Target**

**10 mt $O_2$ / yr**
**or**
**15 mt $H_2O$ / yr**

**Lunar ISRU**

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

**Mars ISRU**

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

**Mars Production Target**

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

# ISRU Perspective I Presentation Takeaways

- **ISRU has significant challenges and knowledge gaps to overcome to be successful**
  - Understanding Resources, Environments, and Environmental Impacts on hardware and processes is Critical

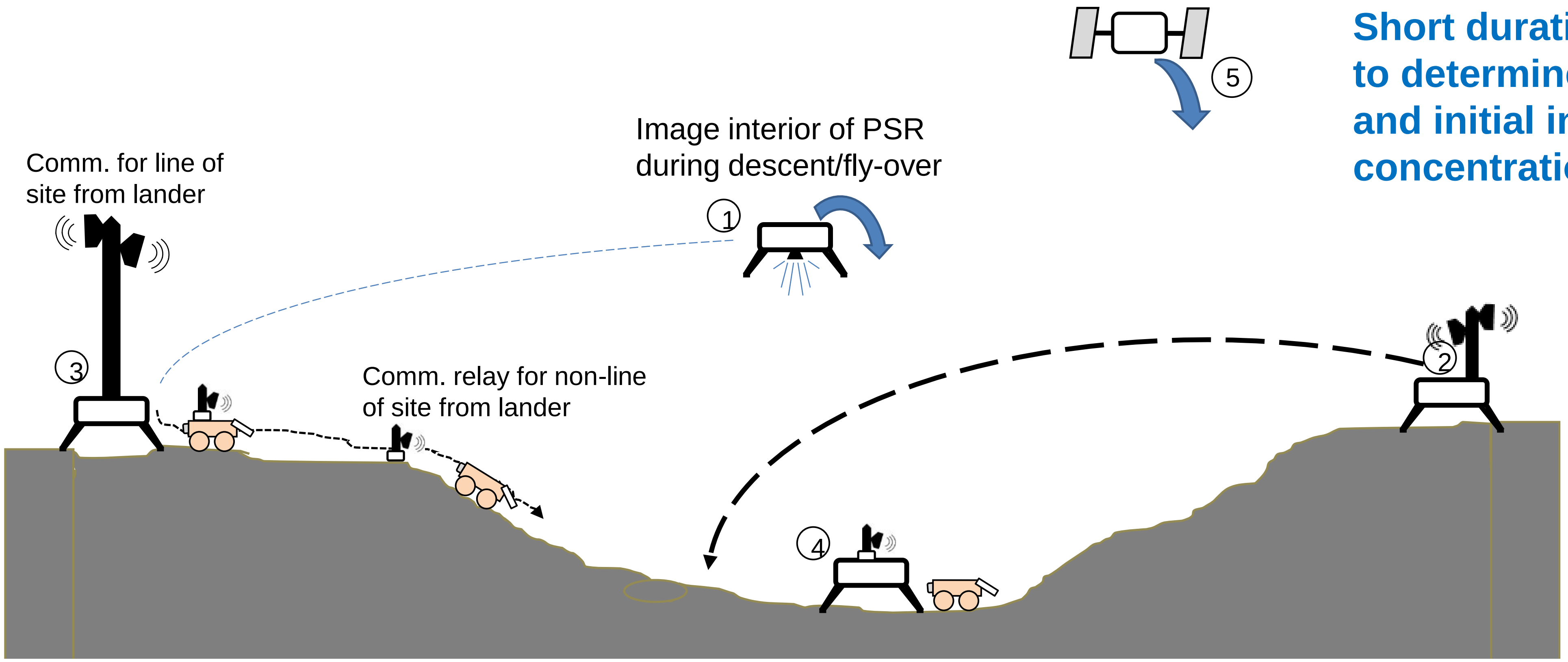
- **Resource assessment instruments are being developed and flown**
  - Most CLPS missions so far are not aimed at polar water/volatile assessment
  - VIPER (and PRIME-1) will provide significant improvement in polar water/volatile understanding
  - More missions to different locations and more resource assessment is needed

- **Technologies are being developed for both Oxygen 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.

- **Lunar ISRU development and operation are Mars Forward**
  - Similar technologies and production rates
  - Deployment and operation on the Moon are


NASA
www.nasa.gov/spacetech

# Polar Resource Assessment – Exploratory Evaluation Options




**Short duration or limited missions to determine if water/volatiles exist and initial information on form and concentration**

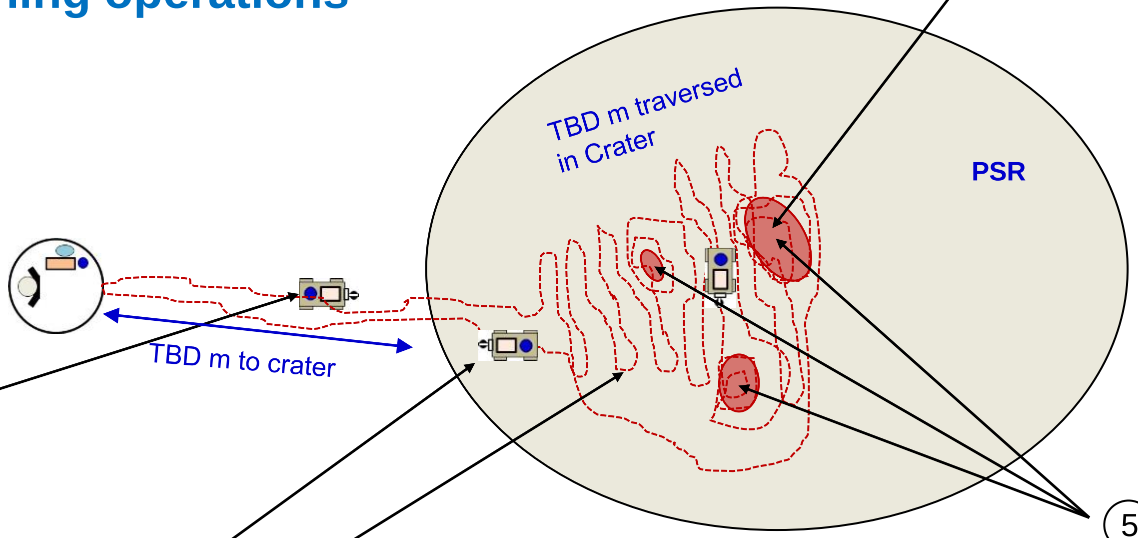
**Landing Options**
- In PSR
- On edge/rim of PSR

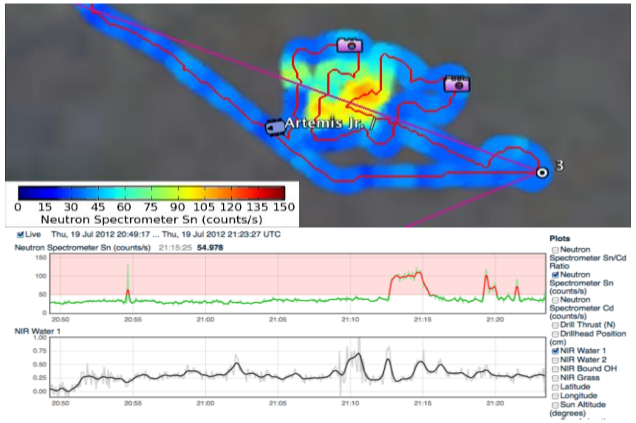
**Power Options**
- Batteries
- Power Beaming
- Power Cables

1. Ejectable/deployable payloads into PSR during descent/fly-over: Payloads are short-lived stationary or mobile assets
2. Ejectable/deployable payloads into PSR after landing near PSR: Payloads are short-lived stationary or mobile assets
3. Payloads deployed after landing next to PSR. Communication from orbit, lander, or relay deployed at PSR rim.
4. Land directly in PSR. Communication from lander. Payload is attached to lander or deployable for short duration operation
5. Fly over PSR. Payload is ejected/deployed for short duration operation

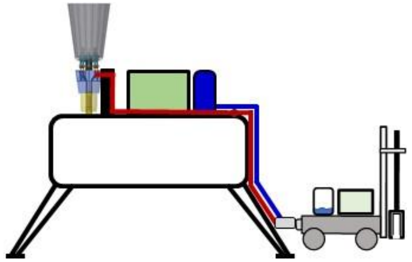
# Polar Resource Assessment – Detailed Resource Mapping Options

## Long duration missions to assess the extent, concentration, and distribution of water/volatiles for mine planning operations




1. Lander images terrain outside and in PSR during descent to update knowledge of terrain
2. Rover traverses into permanently shadowed crater and begins resource assessment
3. Rover measures the following while traversing:
   - Terrain features, rocks
   - Surface minerals,
   - Surface water/hydroxyl,
   - Subsurface hydrogen-sources and potentially subsurface features while traversing
4. Rover traverses in 'search pattern' mode if high concentrations of surface or subsurface hydrogen-source measured
5. Ground personnel map data and identify locations for subsurface resource assessment
6. Rover commanded to specific location and performs geotechnical and direct measurements of subsurface minerals & ice/volatiles
7. Rover returns to lander for periodic recharging
8. Deliver water/volatile samples for analysis and possible crew return to Earth



### Landing Options
- In PSR or in shadowed crater
- On edge/rim of PSR

### Power Options
- Nuclear reactor, batteries on rover
- Advanced RTG on rover with batteries
- Solar arrays in sunlight, batteries on rover
- Solar arrays in sunlight, fuel cell on rover

### Communication & Navigation Options for Rover
- Orbital relay to Earth via Gateway or communication satellite
- Line of site or Non-line of site communication relays from rover-to-lander, with lander-to-Earth direct or thru relay

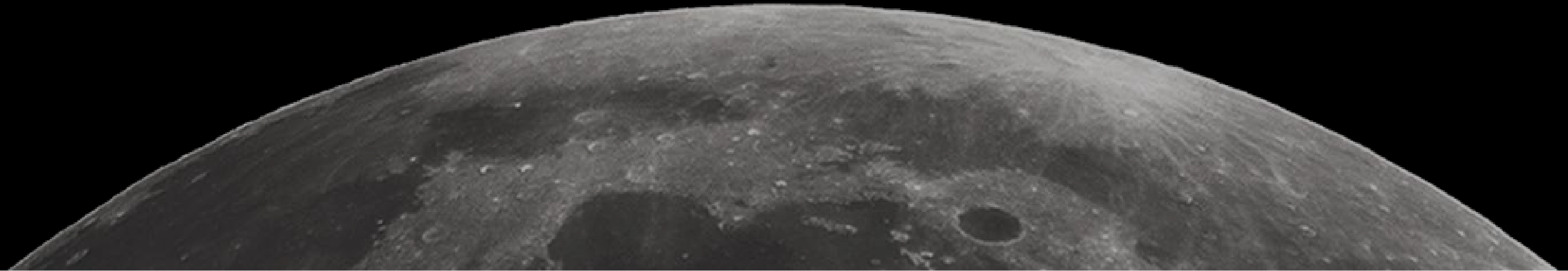
Note: Need near continuous communications to allow for tele-operation

# What is the Lunar Surface Innovation Consortium?

Nationwide alliance of universities, commercial companies, non-profit research institutions, NASA, and Other Government Agencies with a vested interest in our Nation's campaign to establish a sustained presence on the Moon.


## Objectives

- Identify lunar surface technology needs and assess the readiness of relative systems and components.
- Make recommendations for a cohesive, executable strategy for development and deployment of the technologies required for successful lunar surface exploration.
- Provide a central resource for gathering information, analytical integration of lunar surface technology demonstration interfaces, and sharing of results.
- Foster growth of a diverse community and networking among members.



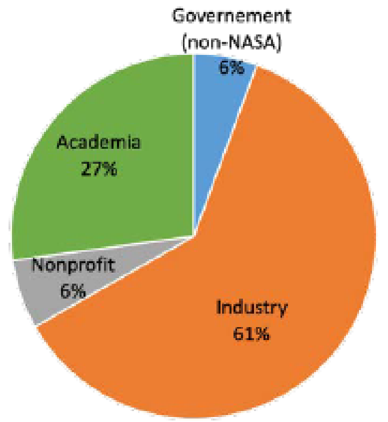
# Lunar Surface Innovation Consortium (LSIC)

## More than 1,000 active participants from over 300 organizations across 44 states, increasing monthly

- Held **3** bi-annual consortium meetings
  - National kick-off Feb. 2020
  - Fall meeting Oct. 2020
  - Spring meeting May 2021
- Conducted **3** thematic Workshops in 2020-2021:
  - **ISRU Supply Demand Workshop** on Sept. 2020
    - over 200 participants
  - **Dust Mitigation Workshop** on Feb. 2021
    - over 350 participants
  - **Lunar Mapping for Precision Landing Workshop** March 2021
    - over 400 participants
- Awarded **6** LuSTR Grants for ISRU and Power
- Active participation in monthly Focus Groups
- Conducted a **Lunar Surface Power Report** to assess the current stage of STMD-funded power-related technologies for LSII
- Conducted **a Lunar Surface In- Situ Resource Utilization (ISRU) Technology and System Integration Assessment** to identify gaps that remain in the development and maturation of ISRU technologies needed to meet NASA goals
- Performed a **Lunar Simulant Assessment** to understand the availability of existing lunar simulants that may be used in technology development efforts for lunar surface operations.
- **Expanded APL support to provide System Integration across all six LSII capability areas**

*Johns Hopkins Applied Physics Lab is the lead for the LSIC and overall System Integrator for LSII*

**LSII Representation**




# University & Public Involvement

## ISRU & Construction Related Challenges

NASA CENTENNIAL CHALLENGES

**Printed 3D Habitat Challenge**

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

**$CO_2$ Conversion Challenge**

- Convert $CO_2$ into sugars
- Phase I completed
- Phase II launched Sept 2019

**Watts on the Moon Challenge**

- Solutions for energy distribution, management, and/or storage
- Launched Sept. 2020

**Break the Ice Challenge**

- Excavate icy regolith in PSR
- Phase I launched Nov. 2020

BIG IDEA CHALLENGE

NASA's Breakthrough, Innovative, and Game-changing (BIG) Idea Challenge

**Lunar PSR Challenge 2020** – completed Jan. 2021

- Exploration of PSR regions
- Technologies to support ISRU in PSRs
- Capabilities to explore & operate in PSRs

**Lunar PSR Challenge Results**

– 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

**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**

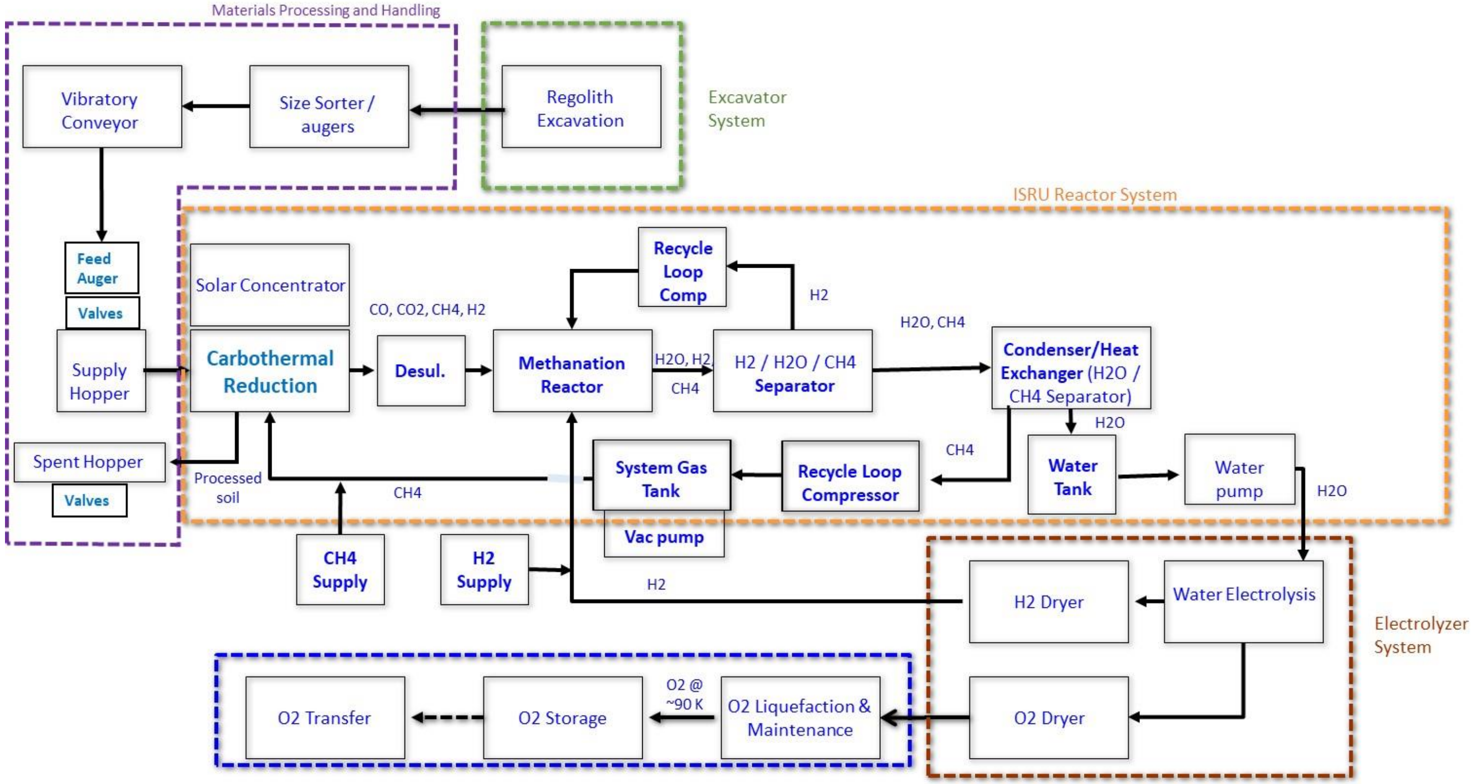
- Yearly, university, started in 2007 following Lunar Excavation Centennial challenge
- Design and build robotic machines to excavate simulated lunar soil (in 30 min.)
- Teams compete at KSC

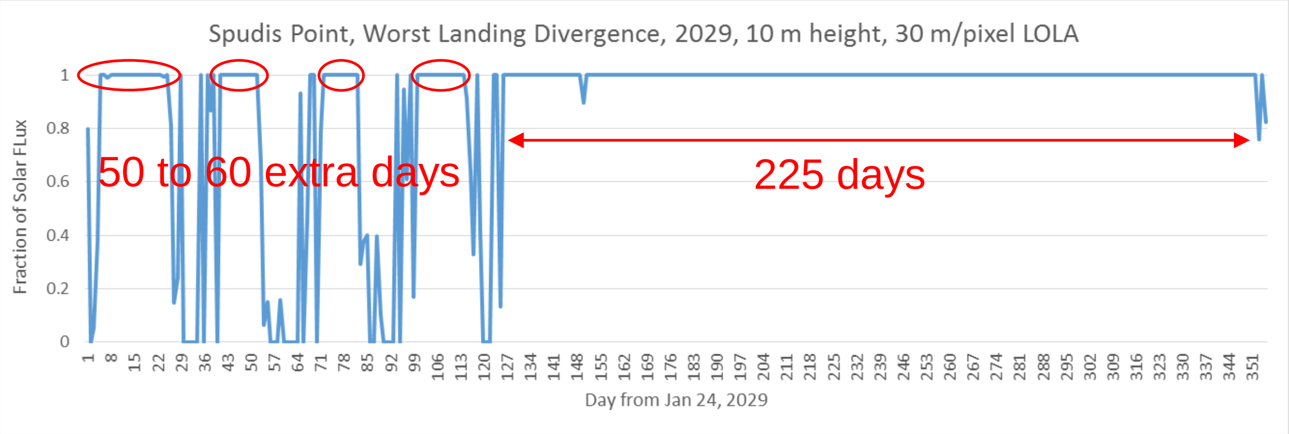
# Oxygen from Regolith – Full Scale System
# Design & Concept of Operation (7.4 continuous months/year)

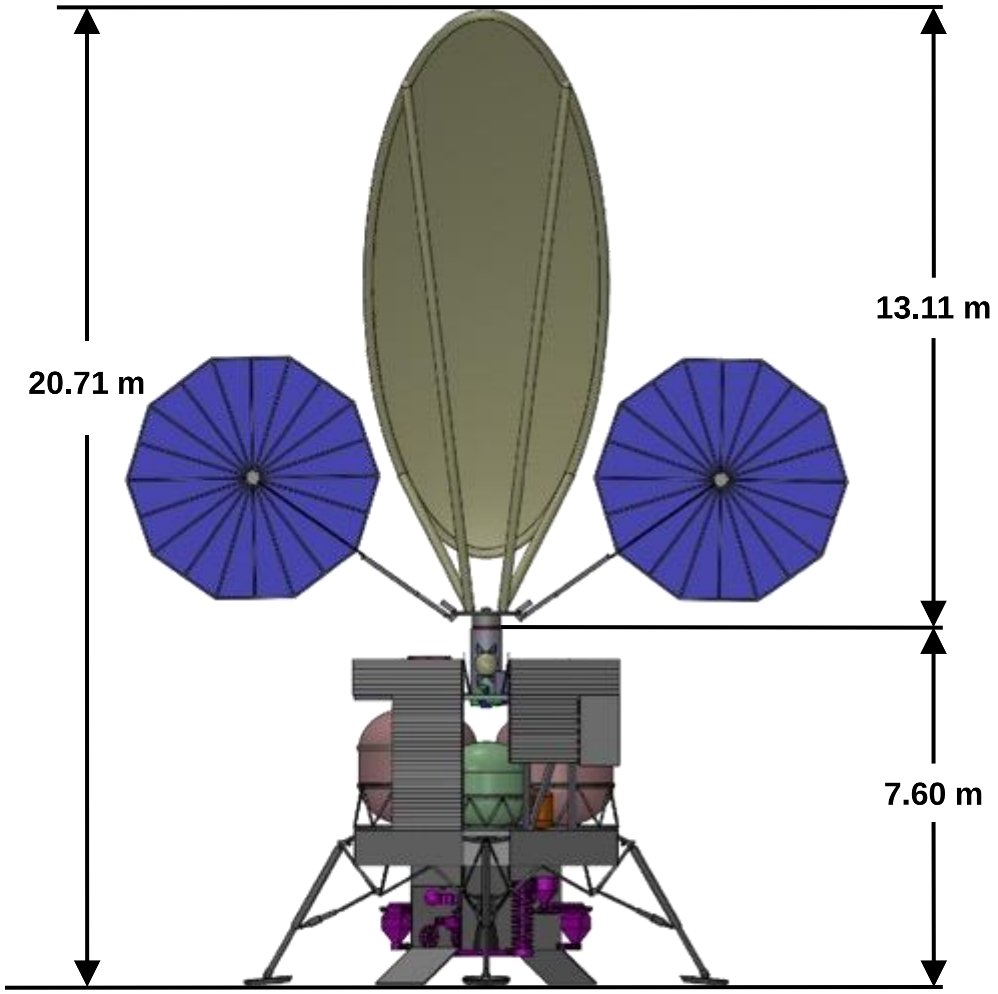
- **Assumed lander had 3.6 mT payload capability and <u>all hardware needed to produce and store $O_2$ are on a single lander</u>**
  - 2nd lander required to deliver mobile O2 storage and transfer unit
- **Each ISRU module (there are two)** produces 15.6 kg of $O_2$ per day (3500 mt $O_2$ per year per module)
- ISRU plant, excavation zone, and dump zone form triangle with 100 m each leg
- Each Excavator
  - Provides 4 deliveries of 35 kg per day to ISRU plant (20 mins total per delivery)
  - Provides 3 disposal runs of 40 kg per day to clear out the two ISRU modules (17 mins total per disposal run)
  - Is charged every 4.5 days (1 kWhr discharged maximum 80% - 50 charge cycles per operating year)
  - Operates via tele-operation/supervised-autonomy with a communication link through the lander to Gateway to Earth
- Electrolysis subsystem converts $H_2O$ into $O_2$ and $H_2$
  - 0.65 kg/hr of $O_2$; $H_2$ recycled back to methanation reactor
- **Oxygen is liquefied and stored in the descent stage $LO_2$ tank** (single system for all ISRU modules)
  - 1.3 kg/hr of $O_2$ (total from two ISRU modules) liquefied and placed in lander tanks
- Solar Concentrator: <u>22.2 kWth</u> energy delivered to ISRU reactors (2) via fiber optic at 1800 °C
- Electrical Power: <u>15 kWe</u> (entire system, with 30% growth)
  - Two Ultraflex arrays at 5.4 m diameter
  - Regenerative fuel cell used for nighttime survival during ISRU standby mode (4.6 'winter' months)

# Oxygen from Regolith – Full Scale System

## *Point of Departure* Carbothermal Reduction (7+mT $O_2$/year)



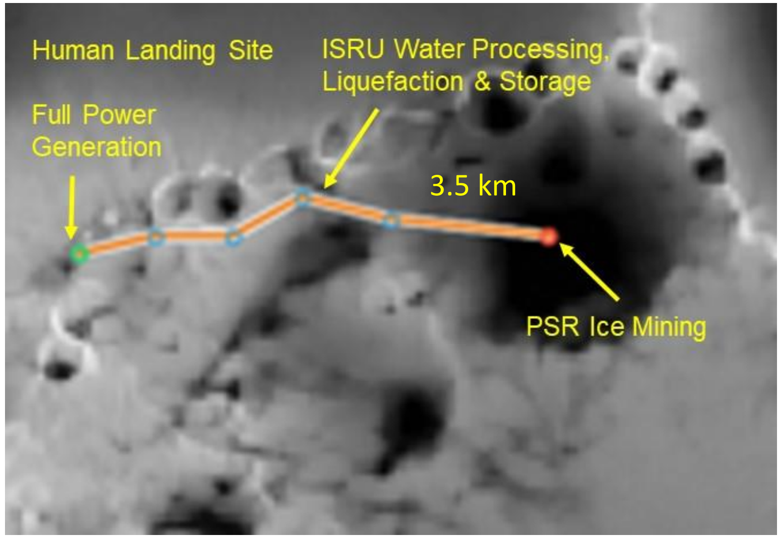

**NOTE: Overall Concentrator height is 11.65 m with a width of 5.24 m**

**NOTE: Both solar arrays create a width of 15.34 m**

# Mining Polar Water: Initial Production Plant Concept

- **Five Systems for Lunar Ice Mining**
  1. Ridge ISRU: Water transfer, cleaning, storage, and electrolysis, and water tankers
  2. Ridge Cryo: Stationary $O_2/H_2$ liquefaction and storage, transfer, mobile $O_2/H_2$ tankers
  3. Ridge ISRU Power : Solar array, regenerative fuel cell (nuclear reactor is optional)
  4. PSR ISRU: excavator(s), regolith processing to extract water, water collection/capture, water transfer
  5. PSR Power: ~25 KW
     - Nuclear reactor & power cart/cable (1.5 km) in PSR
     - Power transfer from Ridge ISRU Power System via power cart/cable (5 km) or power beaming

- **Nominal Mission**
  - 15,000 kg water / year (225 days continuous); 13,336 / 1667 kg ($O_2/H_2$)
    - $H_2$ production is the driver for $O_2/H_2$ propulsion systems
    - 10,000 kg $O_2$/1667 kg $H_2$ = 6:1 Ox/Fuel MR for propulsion
  - Water source: 5% water ice particles mixed and frozen in with regolith, underneath a 20 cm desiccated layer
  - Water transported from PSR to Ridge-based plant via water tanker tbd (>20) times per year
  - Nom. traverse path <15 deg. slopes between Ridge and PSR ISRU Systems




Site selected for Ice Mining Study Only

# The ‘Economics’ of ISRU

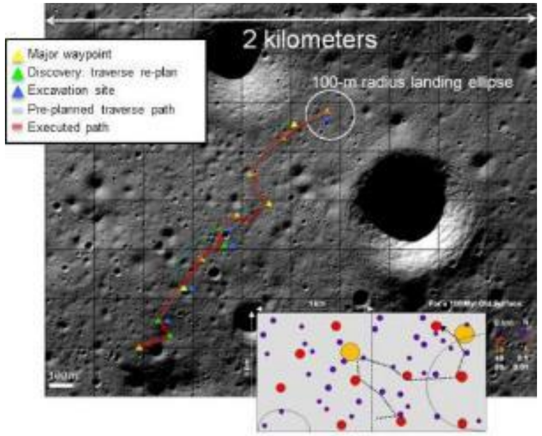
## The Economics of ISRU depends on the Location and Amount/Distribution of the Resource, the Infrastructure and Difficulty of ISRU, and the Amount/Frequency of the product

### Location

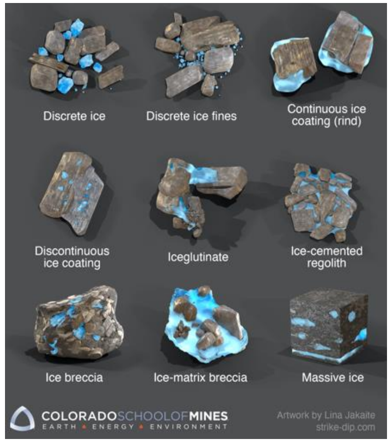
- Resource must be assessable: slopes, rock distributions, surface characteristics, etc.
- Resource must be within ‘reasonable’ distance of mining infrastructure: power, logistics, maintenance, processing, storage, etc.
- Product produced must be within ‘reasonable’ transportation distance of user: Transportation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

**Resource Must Be Known**

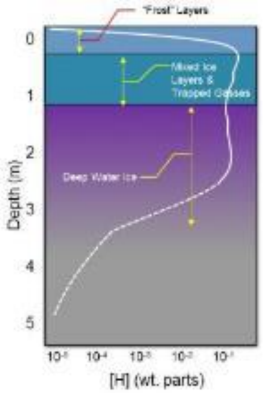
**Need to Evaluate Local Region (1 to 5 km)**



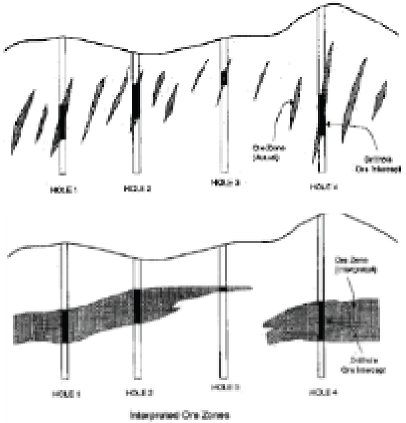

**Need to Determine Form**




**Need to Determine Vertical Profile**




**Need to Determine Distribution**




### Infrastructure and Difficulty of ISRU: infrastructure needed for ISRU must allow for Return on Investment (ROI) for:

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

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

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