# In-Situ Resource Utilization (ISRU) Planning and Update

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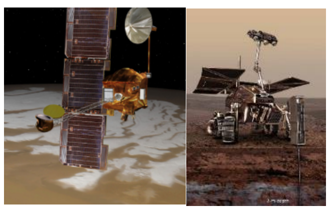
# What is *In Situ* Resource Utilization (ISRU)?

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

## Resources

- Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, metals, alloys, sunlight, etc.
- Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.

## Resource Assessment (Prospecting)

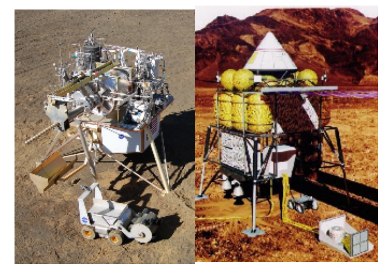


Assessment and mapping of physical, mineral, chemical, and water resources, terrain, geology, and environment

## Resource Acquisition

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

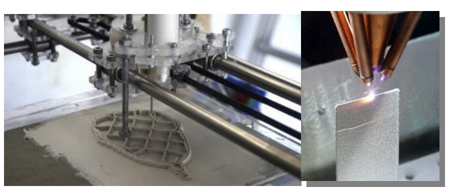
## Resource Processing/ Consumable Production



Conversion of acquired resources into products with immediate use or as feedstock for construction & manufacturing

- Propellants, life support gases, fuel cell reactants, etc.

## *In Situ* Manufacturing



Production of replacement parts, machines, and integrated systems from feedstock derived from one or more processed resources

## *In Situ* Construction

Civil engineering, infrastructure emplacement and structure construction from *in situ* derived materials

- Radiation shields, landing pads, roads, berms, habitats, etc.

## *In Situ* Energy

Generation and storage of electrical, thermal, and chemical energy with *in situ* derived materials

- Solar arrays, thermal storage and energy, chemical batteries, etc.

- **'ISRU' is a capability involving multiple elements to achieve final products**
- **'ISRU' does not exist on its own.** Must connect and tie to users/customers of ISRU products

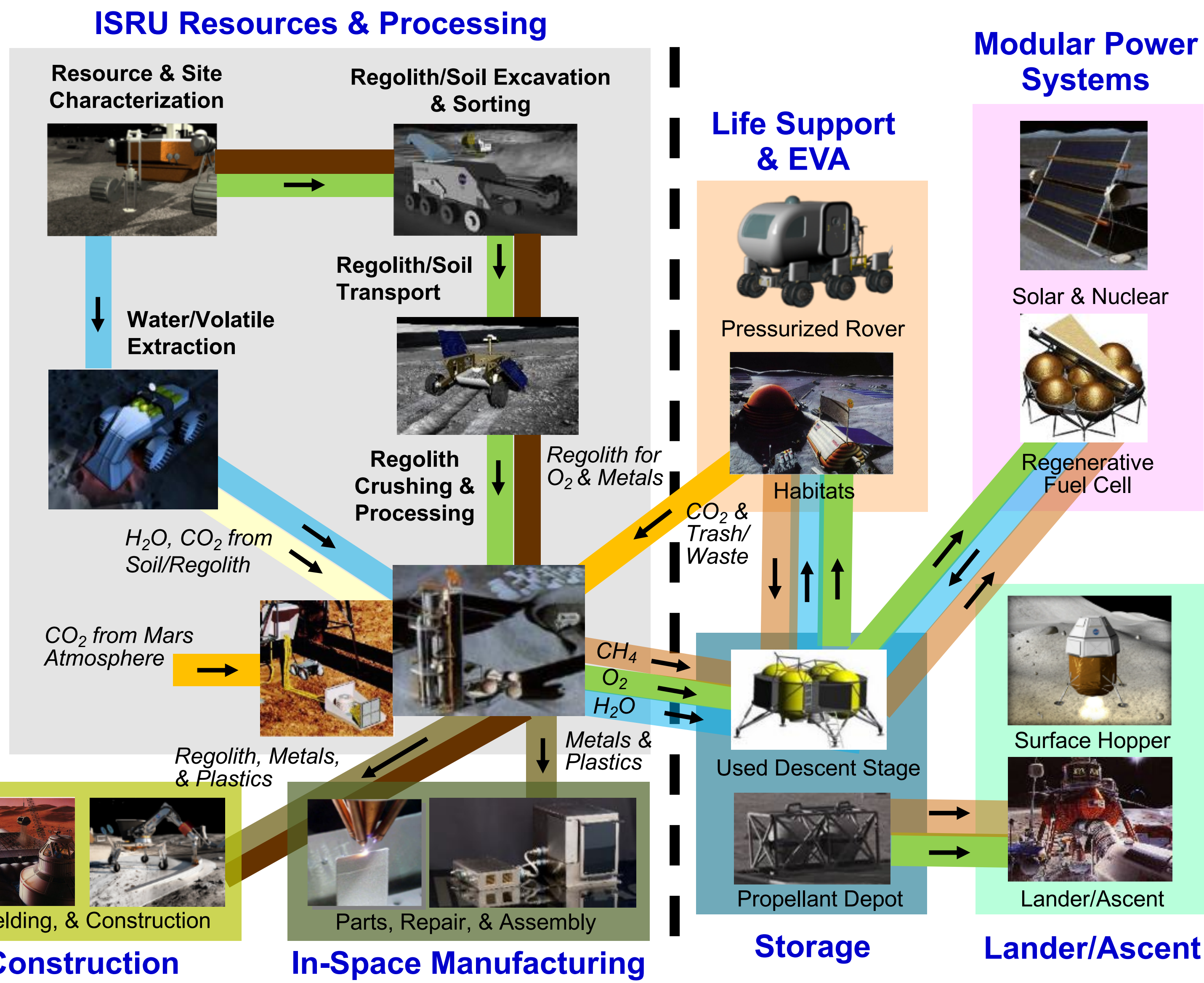
# ISRU Integrated with Exploration Elements
## (Mission Consumables)

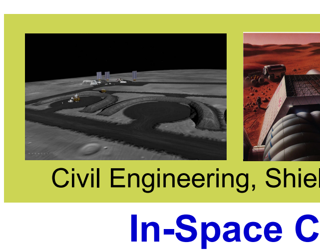
**ISRU Functions & Elements**

- Resource Prospecting/ Mapping
- Excavation
- Regolith Transport
- Regolith Processing for:
  - Water/Volatiles
  - Oxygen
  - Metals
- Atmosphere Collection
- Carbon Dioxide/Water Processing
- Manufacturing
- Civil Engineering & Construction

**Support Functions & Elements**

- Power Generation & Storage
- $O_2$, $H_2$, and $CH_4$ Storage and Transfer



# ISRU: Make It vs Bring It!

## *It Changes How We Explore Space*

### Increases Mission Performance

- **Launch mass savings/Lander size reduction** (>7.5 kg saving per 1 kg produced on Moon/Mars surface)
- Longer stays, increased EVA, or increased number of crew over baseline with ISRU consumables
- **Increased payload-to-orbit** or delta-V for faster rendezvous with fueling of ascent vehicle
- Increased and more efficient surface nighttime and mobile fuel cell power architecture with ISRU

### Increases Sustainability and Decreases Life Cycle Costs

- **Reuse of landers** with in-situ propellants can provide significant cost savings
- Enables in-situ growth capabilities in life support, habitats, powers, etc.
- Enables path for commercial involvement and investment

### Reduces Mission and Crew Risk

- Minimizes/eliminates life support consumable delivery from Earth – Eliminates cargo delivery failure issues & functional backup to life support system
- Increases crew radiation protection over Earth delivered options – *In-situ* water, plastic, and/or regolith
- Can minimize impact of shortfalls in other system performance – Launch vehicles, landers, & life support
- Minimizes/eliminates ascent propellant boiloff leakage issues – *In-situ* refueling
- Minimizes/eliminates landing plume debris damage – Civil engineering and construction
- Decreased logistics and spares brought from Earth – *In situ* manufacturing

### Increases Science

- Greater surface location and science sample collection access thru in-situ fueled hoppers
- Greater access to subsurface samples thru ISRU drilling, excavation, and trenching capabilities
- Increased science payload per mission by reducing launch payload mass/consumables

***ISRU Must Be Considered from the Start or Benefits & Cost Reductions are Minimized***

# ISRU: Make It vs Bring It!

## *It Changes How We Explore Space*

Extra Benefits with Water Resources

### Increases Mission Performance

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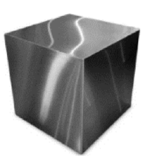
# Main *Natural* Space Resources of Interest

| | Moon | Mars | Asteroids | Uses |
|---|---|---|---|---|
| **Water** | Icy Regolith in Permanently Shadowed Regions (PSR)<br>Solar wind hydrogen with Oxygen | Hydrated Soils/Minerals: Gypsum, Jarosite, Phylosilicates, Polyhdrated Sulfates<br>Subsurface Icy Soils in Mid-latitudes to Poles | Subsurface Regolith on C-type Carbonaceous Chondrites | ▪ Drinking, radiation shielding, plant growth, cleaning & washing<br>▪ Making Oxygen and Hydrogen |
| **Oxygen**   | Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite | Carbon Dioxide in the atmosphere (~96%) | Minerals in Regolith on S-type Ordinary and Enstatite Chondrites | ▪ Breathing<br>▪ Oxidizer for Propulsion and Power |
| **Carbon**  | ▪ CO, $CO_2$, and HC's in PSR<br>▪ Solar Wind from Sun (~50 ppm) | Carbon Dioxide in the atmosphere (~96%) | Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites | ▪ Fuel Production for Propulsion and Power<br>▪ Plastic and Petrochemical Production |
| **Metals**  | Minerals in Lunar Regolith<br>▪ Iron/Ti: Ilmenite<br>▪ Silicon: Pyroxene, Olivine, Anorthite<br>▪ Magnesium: Mg-rich Silicates<br>▪ Al:: Anorthitic Plagioclase | Minerals in Mars Soils/Rocks<br>▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite<br>▪ Silicon: Silica, Phyllosilicates<br>▪ Aluminum: Laterites, Aluminosilicates, Plagioclase<br>▪ Magnesium: Mg-sulfates, Carbonates, & Smectites, Mg-rich Olivine | Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids | ▪ *In situ* fabrication of parts<br>▪ Electical power transmission |

**Similar Resources and Needs Exist at Multiple Locations**

# Moon, Mars, & Near Earth Objects (NEOs)

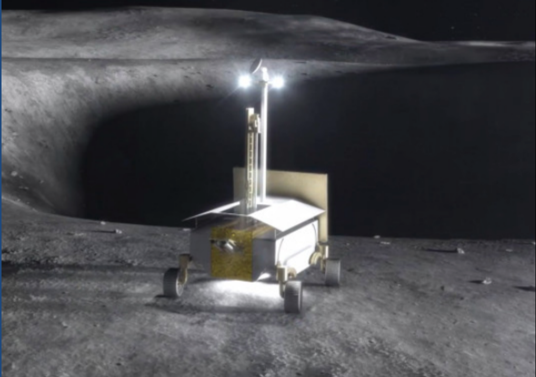
| | Moon | Mars | NEO |
|---|---|---|---|
| Gravity | 1/6 g | 3/8 g | Micro-g |
| Temperature (Max)<br>(Min.)<br>(Min. Shade) | 110 °C/230 °F<br>-170 °C/-274 °F<br>-233 °C/-387.4 °F | 20 °C/68 °F<br>-140 °C/-220 °F | 110 °C/230 °F<br>-170 °C/-274 °F<br>-233 °C/-387.4 °F |
| Solar Flux | 1352 W/m$^2$ | 590 W/m$^2$ | Varied based on distance from Sun |
| Day/Night Cycle | 28+ Days - Equator<br>Near Continuous Liight or Dark - Poles | 24.66 hrs | Varied - hrs |
| Surface Pressure | 1x10$^{-12}$ torr | 7.5 torr | 1x10$^{-12}$ torr |
| Atmosphere | No | Yes<br>$CO_2$, $N_2$, Ar, $O_2$ | No |
| Soil | Granular | Granular & clay; low hydration to ice | Varied based on NEO type |
| Resources | <br>Regolith (metals, $O_2$)<br><br>$H_2O$/Volatile Icy Soils | Atmosphere ($CO_2$)<br>Granular Soil<br>Hydrated Minerals<br>$H_2O$ Icy Soils | <br>Regolith (metals, $O_2$)<br>Hydrated Soil/Minerals<br>$H_2O$/Volatile Icy Soils |

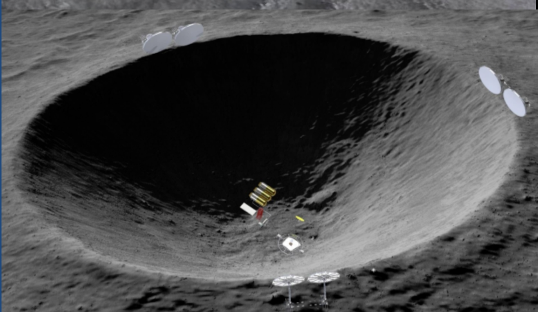
[ ] = Denotes similarities

- **The Moon has aspects in common with Mars and NEOs/Phobos**
- **All destinations share common technologies, processes, and operations**
- **NEO micro-gravity environment is the largest difference between destinations**

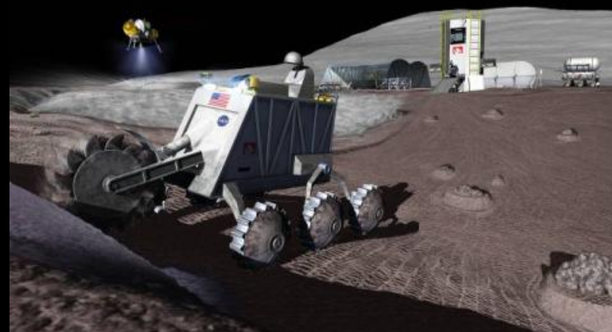
# Lunar ISRU Mission Concepts and Applications

**Resource Prospecting & Polar Water/Volatile Mining**



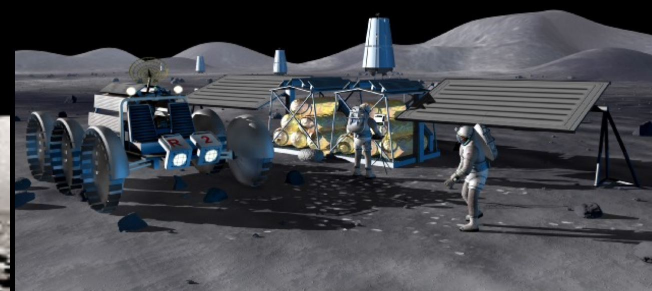


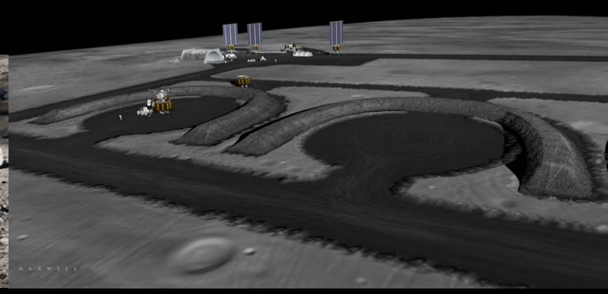
**Excavation & Regolith Processing for Oxygen and Metal Production**



**Hardware Repurposing & Reuse**

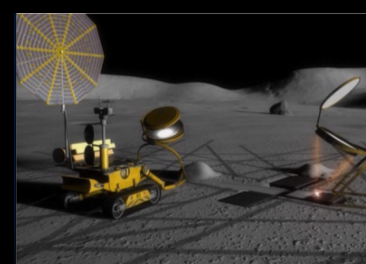
**Consumable Depots & Refueling Landers & Rovers**





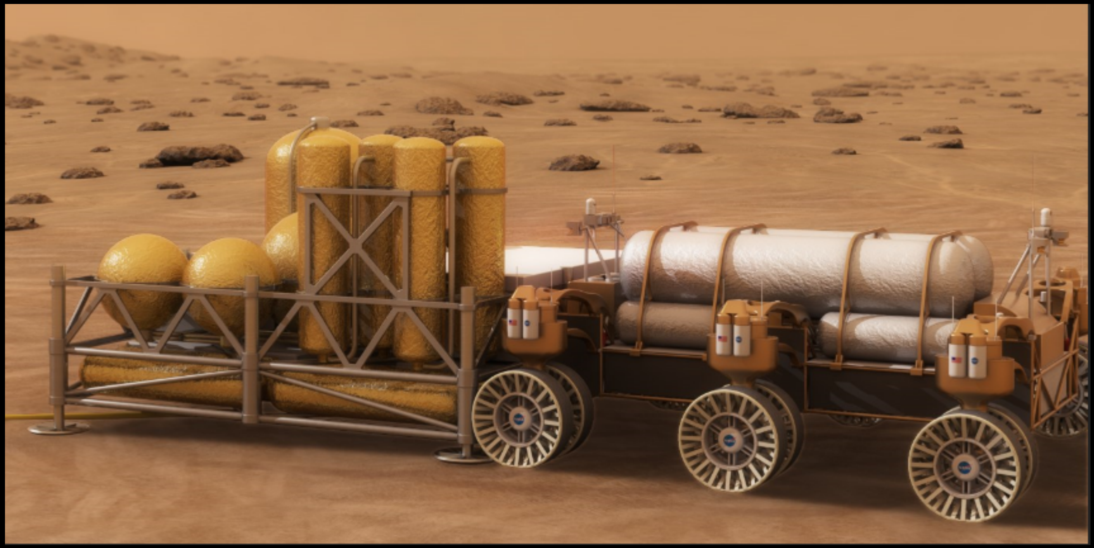
**Landing Pad, Berm, Road & Habitat Construction**

**Thermal Energy Storage**



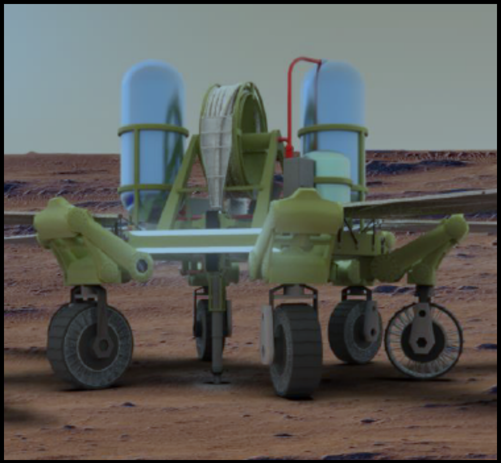
# Mars ISRU Mission Concepts and Applications

## Atmosphere Processing – Oxygen/Methane Liquefaction & Storage



## Mars Ice Drilling & Extraction

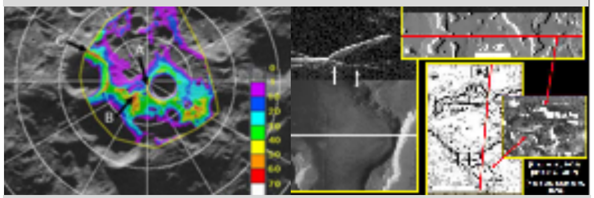
## Excavation & Soil Processing for Water



# ISRU Strategic Vector

## Today
(Technology & Feasibility)

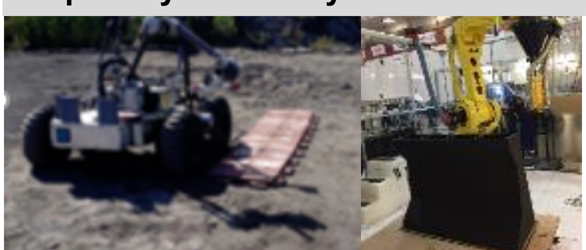
**Orbital Data with Limited/No Surface Water Resource Info**



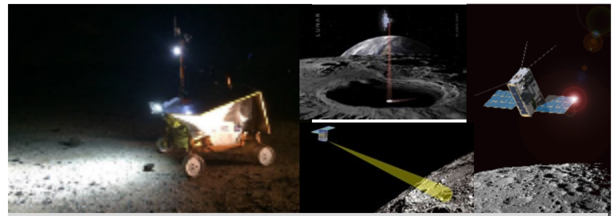
**Technology/Concept Option Evaluation**

**Short Duration System Tests**

**Capability Feasibility Demonstrated**



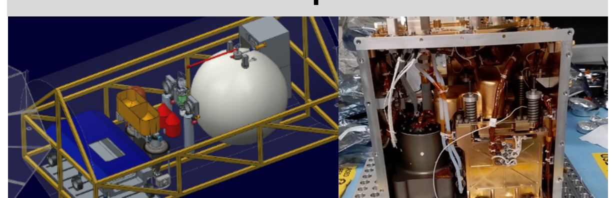
## Near-Term
(Ground Dev. & Flight Demos/Prospecting)



**Surface Resource & Water Characterization/Prospecting**

**Environmental & Long-Duration Ground Testing**

**Technology Selection & System Development**



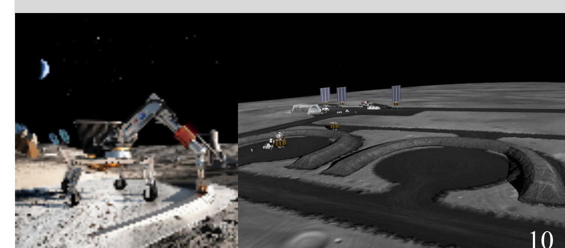
**Flight Demonstrations & Pilot Plants for Mission Enhancement**

## Goal
(Mission Utilization)

**Oxygen & Propellant Production for Transportation**

**Consumables for Regenerative Power & Life Support**

**Manufacturing & Construction w/ In Situ Derived Materials**



# Mission Consumables from ISRU

## Oxygen from Regolith vs Polar Water/Volatiles

- **Oxygen from Regolith**
  - **Can be incorporated into the architecture from the start with low-moderate risk**
    - Resource characteristics and parameters are reasonably well known
    - Multiple approaches for extraction possible; 2 demonstrated to TRL 4-5 for short periods of time
  - **Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth)**
  - Experience from regolith excavation, beneficiation, and transfer applicable to mining Mars hydrated soil/minerals for water and In Situ Manufacturing and Construction

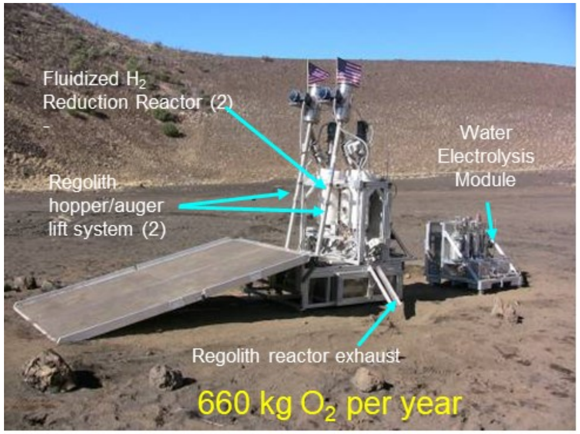
- **Water and Volatiles from Polar Regolith**
  - **Polar Water/Volatiles is "Game Changing" and Enables Long-term Sustainability**
    - Availability of water for propellants can strongly influence propulsion system design (propellant selection and reusability) and transportation architecture (depots, hoppers, lander reuse, etc.)
    - Provides 100% of chemical propulsion propellant mass
    - Reuse of cargo and human landers and transportation elements can reduce long-term mission costs and enable new mission concepts; **Direct to Gateway possible**
    - Provides significantly more options for radiation protection, food production, etc. over what is available from lunar regolith

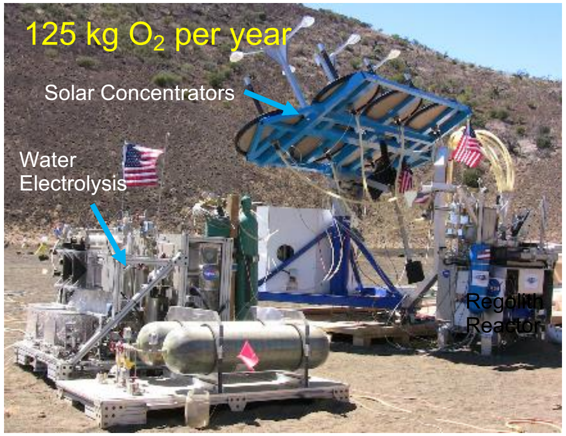
**NASA should pursue both Development and Insertion of both**

- **Oxygen from Regolith mining for immediate benefits with low-moderate risk**
- **Prospecting and Polar Ice/Volatiles mining for Long Term Sustainability**

# Oxygen from Lunar Mineral Oxides

- **Lunar regolith is >40% oxygen ($O_2$) by mass**
  - Four primary mineral types on the Moon: Ilmenite, Pyroxene, Olivine, and Anorthite
  - Ilmenite and pyroclastic glasses are the easiest lunar materials to reduce/extract $O_2$
- **Over 20 processes have been identified to extract the oxygen**
  - Several have been evaluated in the lab to TRL 3 at subscale
  - As processing temps increase, $O_2$ yield increases, and technical and engineering challenges increase.
- **Two processes have been developed to TRL 4-5 at human mission relevant scale**
  - **Hydrogen ($H_2$) Reduction:**
    - Reduces iron oxide to iron and water with hydrogen at >900 C; regolith stays granular
    - Water is electrolyzed: $O_2$ is stored and $H_2$ is recycled
    - 1 to 5 kg of $O_2$ extracted per 100 kg of bulk/unrefined regolith depending on location (1 to 5 wt% eff.)
    - Extraction efficiency can be increased with mineral beneficiation to increase iron oxide content
  - **Carbothermal ($CH_4$) Reduction**
    - Reduces silicates at >1600 C to produce carbon monoxide (CO) and $H_2$; regolith is molten
    - CO and $H_2$ are converted to $CH_4$ and water: methane is recycle, water is electrolyzed
    - 10 to 15 kg of $O_2$ extracted per 100 kg of bulk/unrefined regolith (10 to 15 wt% eff.)



# Lunar ISRU Technology, System, & Flight Development in the 2000's

## Development Aimed at Oxygen for Life Support Backup & Prospecting for Polar Water

### Resource Characterization & Mapping
- Lunar polar ice/volatile characterization: RESOLVE

### Mission Consumable Production
- Regolith Excavation, Transfer, & Preparation
  - Excavation:  bucketwheel, bucketdrum, scoop
  - Pneumatic regolith transfer
  - Size Sorting
  - Mineral Beneficiation
- Oxygen ($O_2$) Extraction from Regolith
  - Hydrogen ($H_2$) Reduction
  - Carbothermal ($CH_4$) Reduction
  - Molten Oxide Electrolysis
  - Ionic Liquids
- Water and Fuel from Trash
  - Steam Reforming
  - Combustion/Pyrolysis
- Water Processing
  - Water Electrolysis
  - Water Cleanup

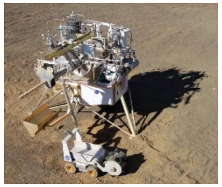


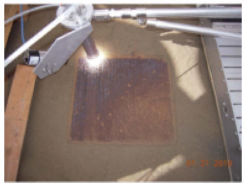
### Energy Generation, Storage & Transfer
- Solar Concentrators
- Heat Pipes

### Civil Engineering & Surface Construction
- Area clearing, leveling
- Berm building
- Surface Sintering

### Systems
- 2008 Analog Field Test
  - Hydrogen Reduction of Regolith for $O_2$ : PILOT & ROxygen
  - Excavation Rovers:  Cratos & LMA Bucketdrum
  - Polar Ice Prospecting:  RESOLVE on CMU rover
- 2010 Analog Field Test
  - Carbothermal Reduction, Solar Concentrators, Water Electrolysis, & $O_2$ Storage
  - Surface Sintering
  - Polar Ice Prospecting:  RESOLVE on CSA rover





# Lunar ISRU Technology Readiness Level (TRL) Advancement

## Significant advancement from 2005 to 2011

| TRL increase in ETDP | At Start | At End | Delta | |
|---|---|---|---|---|
| **System Level** | | | | |
| Lunar Volatile Characterization (RESOLVE) | 1 | 5 | 4 | Advanced to TRL 5/6 since 2011 |
| $H_2$ Reduction of Regolith | 2-3 | 5 | 2-3 | |
| $CH_4$ Reduction of Regolith | 2-3 | 5 | 2-3 | |
| Molten Oxide Reduction of Regolith | 2 | 3 | 1 | |
| Trash Processing for Water/Methane Production | 2 | 2-3 | 0-1 | Advanced to TRL 4 since 2011 |
| **Subsystem Level** | | | | |
| Regolith Transfer & Handling | | | | |
| Regolith Transport Into/Out of Reactor | 2 | 5 | 3 | |
| Beneficiation of Lunar Regolith | 2-3 | 2-3 | 0-1 | |
| Size Sorting of Lunar Regolith | 2-3 | 2-3 | 0-1 | |
| Oxygen Extraction From Regolith | | | | |
| $H_2$ Reduction of Regolith Reactor | 3 | 5 | 2 | |
| Gas/Water Separation & Cleanup | 2 | 4-5 | 2-3 | Technologies advanced since 2011 |
| $CH_4$ Reduction of Regolith Reactor | 3 | 5 | 2 | |
| $CH_4$ Reduction Methanation Reactor | 3-4 | 4-5 | 1-2 | Technology advanced since 2011 |
| MOE of Regolith Anode/Cathode | 1-2 | 3-4 | 2-3 | |
| MOE of Regolith Molten Mat'l Removal | 1-2 | 3 | 1-2 | |
| MOE Cell and Valving | 2-3 | 3 | 0-1 | |
| Water/Fuel from Trash Processing | | | | |
| Trash Processing Reactor | 2 | 2-3 | 0-1 | Advanced to TRL 4 since 2011 |
| In-Situ Energy Generation, Storage, and Transfer | | | | |
| Solar Thermal Energy for Regolith Reduction | 2 | 5 | 3 | |

# Concept of Operation – Full ISRU $O_2$ Plant

## Hydrogen Reduction – 10 MT $O_2$/yr

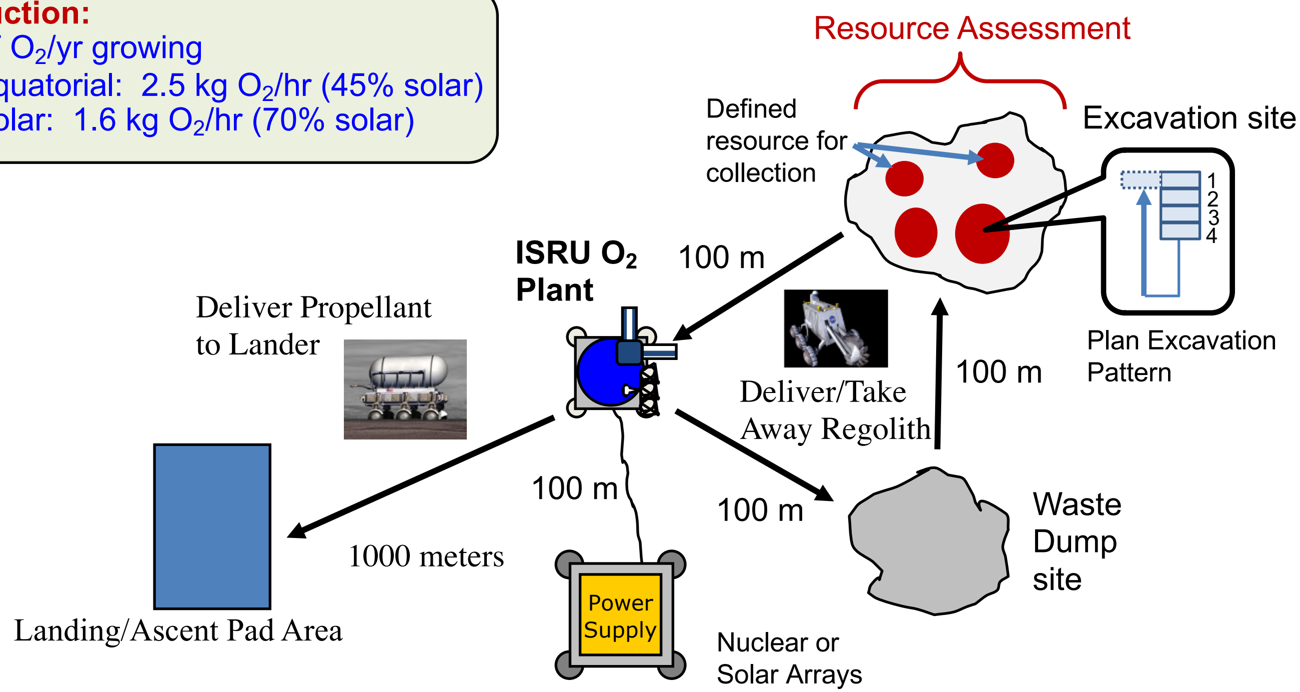
### Excavation & Regolith Delivery

- 2 or 3 small excavators (~80 to 100 kg class)
- Excavate loose soil to depth of ~10 cm
- Deliver multiple loads per day to ISRU plant
  - Store multiple batches in hopper so excavators have time to recharge periodically
  - Include mineral beneficiation on rover or in hopper to increase extraction efficiency
- Take processed ('spent') regolith to dumping zone
- Take discard from beneficiation to separate zone
- Return to excavation zone

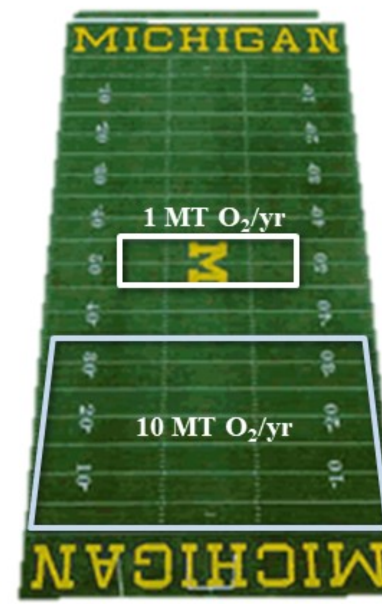
### $O_2$ Production, Storage, & Delivery

- 3 Modules (~3.5 MT $O_2$/yr each) mounted on lander or deployed to the surface
- Regolith processed in batches to extract oxygen ($O_2$) in the form of water ($H_2O$)
  - Reactor work in staggered parallel to maintain continuous production rate
- $H_2O$ is split into $O_2$ and hydrogen ($H_2$)
  - $H_2$ is recycled back to reactor
- Oxygen is liquefied in stored
  - Delivered to Lander via mobile $O_2$ storage unit

**Production:**
10 MT $O_2$/yr growing
- Equatorial: 2.5 kg $O_2$/hr (45% solar)
- Polar: 1.6 kg $O_2$/hr (70% solar)



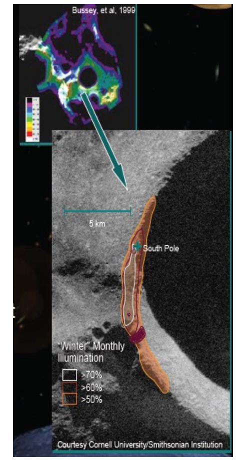

Regolith Excavation Zone
(Down to 10 cm)

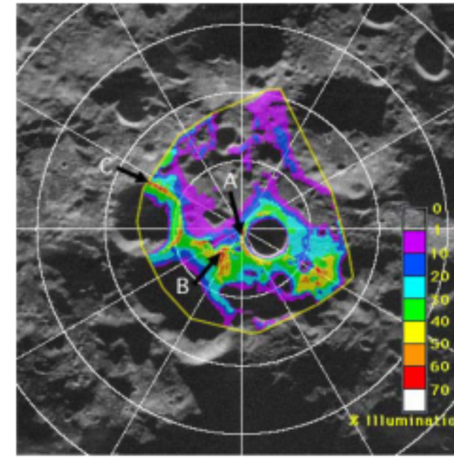


# Lunar Polar Location and Resources

## Polar Locations – *Optimal location for sustained surface operations*

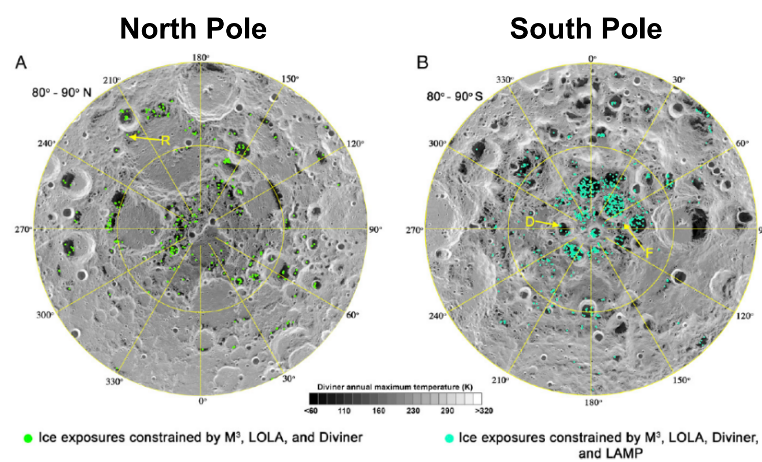
- Areas of near permanent sunlight (>70% sunlight per year)
  - Lower thermal extremes and greater use of solar power
  - Regolith based resources for oxygen and metals;  Highland regolith (iron poor)
- Areas of permanent shadow
  - Cold locations for cryogenic storage, instruments, and thermal energy generation
  - Polar volatiles may include hydrogen, water, ammonia, carbon monoxide, and organics



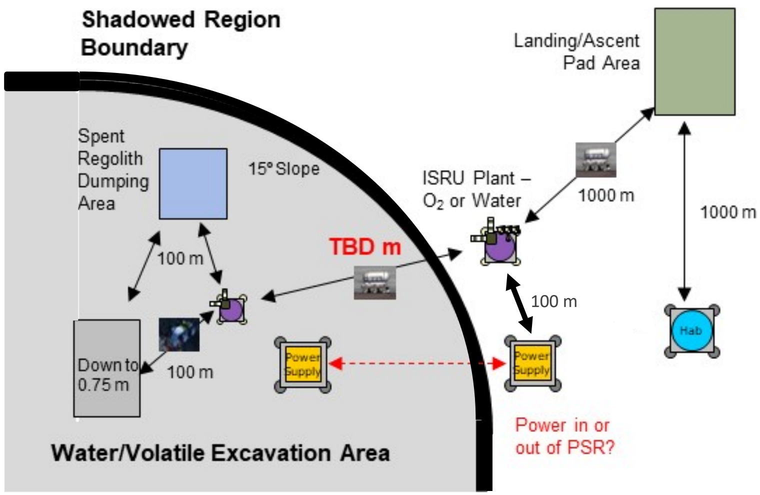




## Polar Water/Volatiles

- LCROSS Impact estimated **5.5 wt%** water in plume
- Green and blue dots show positive results for surface water ice using $M^3$ and LOLA data for the North pole, and $M^3$, LOLA, and LAMP data for the South pole.
- Data points also have maximum annual temperatures of <110 K from Diviner data.
- Spectral modeling shows that some ice-bearing pixels may contain **~30 wt % ice** (mixed with dry regolith)
- Ice detections in the south are clustered near the craters Haworth, Shoemaker, Sverdrup, and Shackleton, while those in the north are more isolated.



# Polar Water/Volatile Extraction



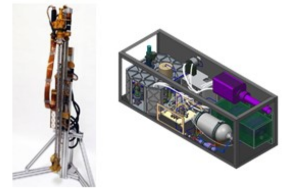

- **Polar Mining Site Selection Criteria**
  1. Surface/Subsurface Volatiles
     - High hydrogen content (LEND instrument)
     - Constant <100 K temperatures 10 cm below surface (Diviner instrument)
     - Surface OH/$H_2O$ ($M^3$, LAMP)
  2. Reasonable terrain for traverse inside and in/out of shadowed region
  3. Long-duration sunlight and hospitable environment nearby for mining and logistics infrastructure

- **Significant Uncertainties in Physical Properties and Resource Distribution**
  - Several technologies & concepts under consideration; Highly dependent on physical/resource properties
  - Technologies are low TRL; limited testing to date
  - **Lunar 'ground truth' data is critical to downselect and finalize development**

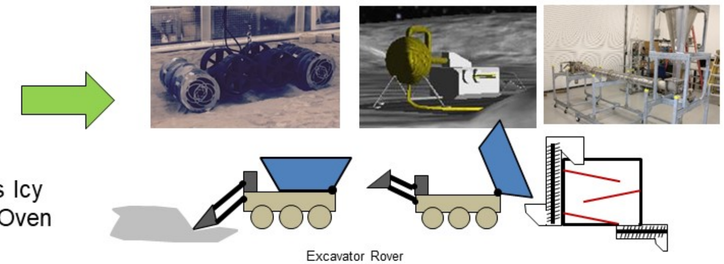
## Potential Approaches to Polar Ice Mining

### Excavation w/ Closed Reactor

Excavator Brings Non-Cemented Icy Regolith to Continuous Feed Reactor-Processor for Extraction

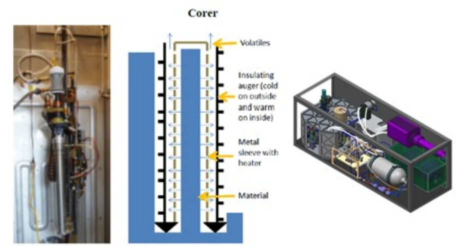


2022 Mission: Auger Brings Icy Regolith to Heated Crucible-Oven

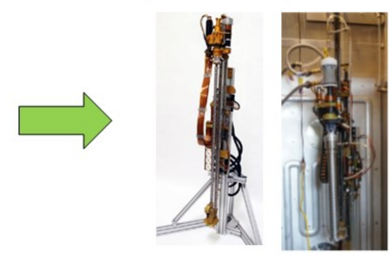



### Downhole – Enclosed Extraction

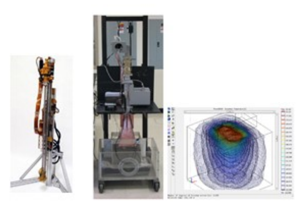
Process in 50 cm steps; Use Auger to clear processed regolith from hole




Auger Down to 50 cm and feed gases to Collector & GC/MS



### Downhole – Open Extraction



Beamed Energy Downhole (Solar or Microwave) and Volatiles Collected

Combine Auger Drilling, Downhole heating via solar thermal energy, and Dome collector

# ISRU Development and Implementation Challenges/Risks

## 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 Operation Challenges

**O1 How to operate in extreme environments?**
Temperature, pressure/vacuum, dust, radiation

**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

## 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 Integration Challenges

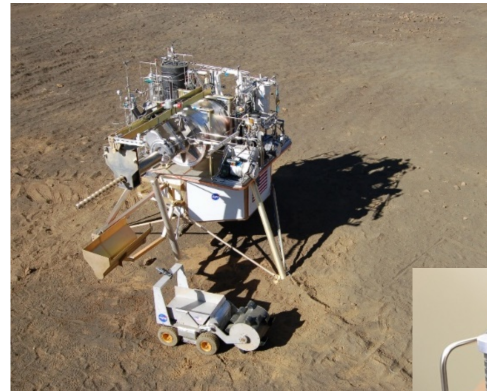
**I1 How are other systems designed to incorporate ISRU products?**

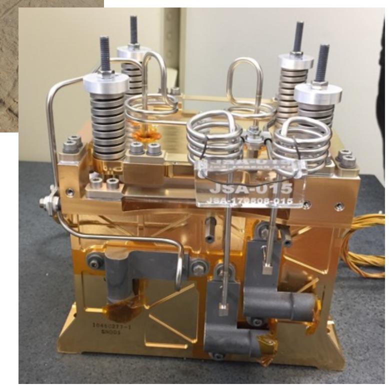
**I2 How to optimize at the architectural level rather than the system level?**

**I3 How to manage the physical interfaces and interactions between ISRU and other systems?**

**Overcoming these challenges requires a multi-destination approach consisting of resource prospecting, process testing, and product utilization.**

# NASA ISRU Development Strategy





### Technology Needed to:
- Prospect for potential resources
- Extract and process those resources into mission critical products (propellants, life support consumables)
- Produce parts, landing pads, and structures from extraterrestrial materials

### Capabilities will Enable:
- Finding and characterizing water resources
- Processing of extraterrestrial resources to produce oxygen (and fuel) for crew ascent and reusable lander and transportation systems
- Commercial involvement in space exploration

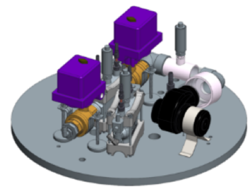
### Development Approach:
- Develop and mature component, subsystem, & systems, and demonstrate them in ground environments
- Mature ISRU technologies to reach system-level TRL 6 to support future flight demonstration missions
- Validate, high fidelity ISRU systems mass, power, & volume for incorporation into architecture analyses
- Maintain a balance of in-house and external work to mature the technologies and capabilities

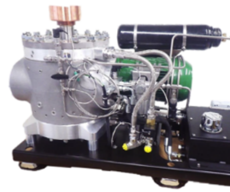
### Path to Operational ISRU:
**ISRU must first be demonstrated (on the ground and on the Moon/Mars) before it can be mission-critical.**
- Subscale Mars atmosphere to oxygen demonstration (MOXIE) flying on Mars 2020 rover
- Subscale demonstrations of critical technologies on Commercial Lunar Payload Services (CLPS) landers (e.g. excavation, mineral beneficiation, regolith processing) in the early to mid 2020’s
- Orbital and lander/rover missions to find and characterize water/volatiles in permanently shadowed craters
- Pilot/Human mission relevant scale demonstrations of ISRU mining and processing for oxygen and water; possibly tied to demonstration of nuclear power on the Moon in the mid 2020’s

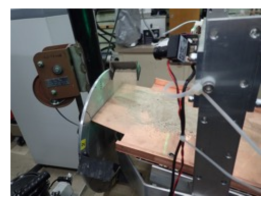
# ISRU Excavation & Chemical Processing Development

## ISRU Technology Project

- **Mars Atmosphere Processing**
  - Dust Filtration: Filter, Electrostatic, & Cyclone
  - $CO_2$ Collection & Pressurization: Freezing & Rapid Cycle Adsorption
  - Sabatier Reactor Design/Modeling/Testing for ISRU
  - Solid Oxide Electrolysis Design/Modeling/Testing
  - Gas separation Technologies: $CO/CO_2$ & $CH_4/H_2$
- **Extraterrestrial Material Excavation**
  - Surface granular material lab reconditioned
  - Granular material excavation with bucketdrum & scoopers
  - Consolidated/hard excavation testing of single tooth ripper
- **Extraterrestrial Material Processing for Water**
  - Open reactor
  - Closed continuous-feed auger reactor
  - Microwave granular material heating reactor
  - Subsurface ice extraction (Rodwell) concept evaluation
  - Water collection & cleanup
- **System Engineering, Integration, and Testing**
  - Modeling & Analysis
  - Simulants

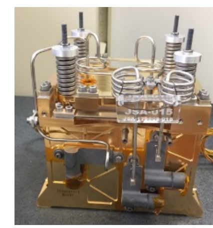


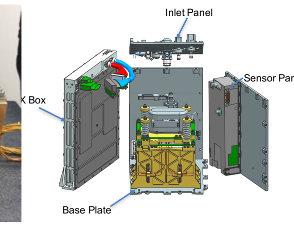




## Mars OXygen Isru Experiment (MOXIE)

- **Payload on Mars 2020 rover**
  - Make $O_2$ from Atm. $CO_2$: ~0.01 kg/hr $O_2$; 600 to 1000 W-hrs; 15+ sols of operation
  - Demonstrate Scroll Compressor and Solid Oxide Electrolysis technologies






## University Challenges

- **Mars Ice Challenge**
  - 10 Teams in 2018
  - Modified to Moon-Mars Challenge for 2019
- **Robotic Mining Competition**

## ISRU NextSTEP BAA

**Studies – Track 1**

- Enhancing Lunar Exploration with ISRU Strategies – Blue Origin
- ISRU Affordability Thresholds – ULA
- Integrated Architecture Trade Studies on ISRU – Uni. Of Illinois
- Water Electrolysis – UTC Aerospace Systems

**Components – Track 2**

- Compact High Efficiency Dust Filter – BlazeTech
- Hydrogen & Methane Separator – Skyhaven Systems
- ISRU-derived Water Purification and $H_2$ $O_2$ Production – Paragon Space
- Advanced Alkaline Electrolyzer – Teledyne Energy

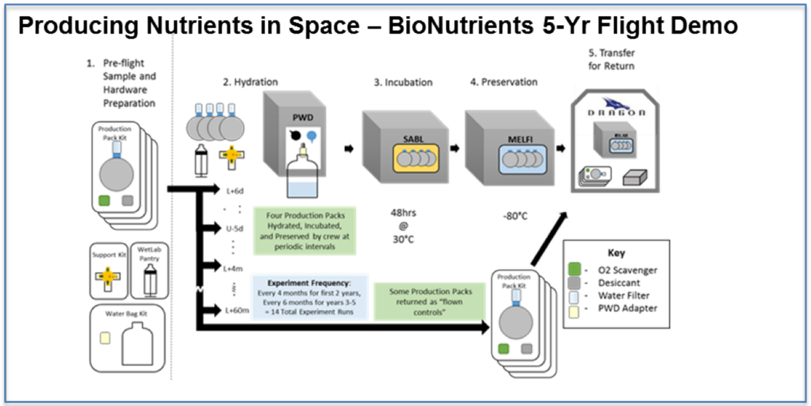
**Subsystems – Track 3**

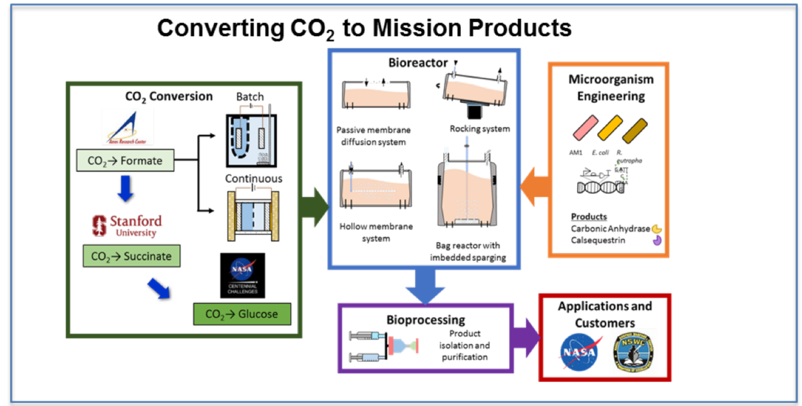
- RedWater: Extraction of Water from Mars Ice – Honeybee Robotics
- Production of $O_2$ & Fuels from In Situ Resources on Mars – OxEon Energy

# ISRU-Related Biological Processing Technology Development

## Synthetic Biology

- This project is developing methods to manufacture needed, complex compounds in space. Novel methods are also being created to use $CO_2$ as a feedstock for bio-manufacturing
- Develop a prototype system that rapidly converts $CO_2$ to microbial feedstock with subsequent bio-production of valuable mission products.




## Center for the Utilization of Biological Engineering in Space (CUBES)

- STMD Space Technology Research Institute (STRI) BioManufacturing Topic
  - Microbial Media and Feedstocks Division
  - Biofuel and Biomanufacturing
  - Food and Pharmaceutical Synthesis
  - Systems Design and Integration
- $15 M Total - $3M/year for 5 years.
- One year complete – Arkin presented to NASA Advisory Council

CUBES

Berkeley University of California · Stanford University · UF University of Florida · UtahState University · UC Davis University of California · PSI Physical Sciences Inc.

## "Carbon Dioxide Conversion Centennial Challenge"

- STMD Centennial Challenge Program – Developing
- $1.0M challenge regarding $CO_2$-derived products that support microbial growth.
- Over 1000 registrants – worldwide attention.

NASA $CO_2$ Conversion Challenge

# Civil Engineering and *In Situ* Construction

## Areas Clearing/Berm Building

- Moses Lake, 2007

## Landing Pad Construction: (NASA, PISCES, Honeybee Robotics)

Grading & Leveling Blade

Compactor Roller

Paver Deployment

Completed Landing Pad

Images Courtesy Rodrigo Romo, Pacific Int'l Space Center for Exploration Systems (PISCES)

## Additive Construction with Mobile Emplacement (ACME)

- 2D and 3D printing on a large (structure) scale using in-situ resources as construction materials to help enable on-location surface exploration

## NASA Centennial Challenge:

3D Printed Habitat ($2.5 Million Prize)


Phase 1: Concept


Phase 2: Structural Member Competition

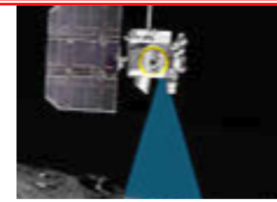
Phase 2: 1.5 m Printed Dome

**Phase 3: Structure Fabrication – April 2019**

## Automated Construction for Expeditionary Structures (ACES) - NASA with U.S. Army Corps of Engineers

- 3D print large structures to support deployment in remote areas

# Current NASA Lunar ISRU-Related Research & Missions Underway & Under Development



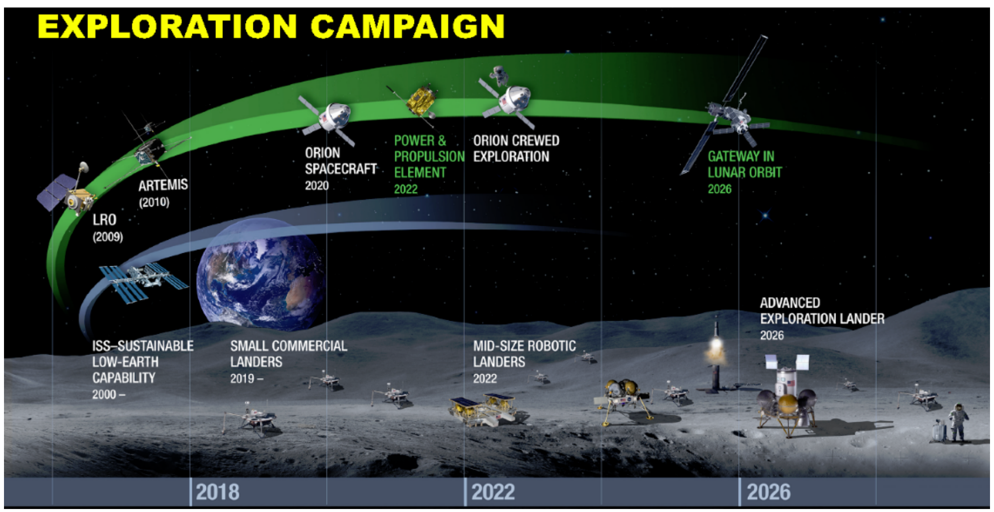
## Lunar Reconnaissance Orbiter (LRO) – 2009 to Today

## Korea Pathfinder Lunar Orbiter (KPLO) - 2020

- ShadowCam Map reflectance within permanently shadowed craters

## Science/Prospecting Cubesats (SLS EM-1 2019)

- Lunar Flashlight: Near IR laser and spectrometer to look into shadowed craters for volatiles
- Lunar IceCube: Broadband InfraRed Compact High Resolution Explorer Spectrometer
- LunaH-MAP: Two neutron spectrometers to produce maps of near-surface hydrogen (H)
- Skyfire/LunIR: Spectroscopy and thermography for surface characterization
- NEA Scout: Multispectral camera for NEA morphology, regolith properties, spectral class




## Commercial Lunar Payload Services (CLPS)

- Request for Proposals for 50, 200, and 500 kg class lander missions

## Human Lunar Landers

- Series of landers aimed at increasing payloads to 5000+ kg and human-rating for crewed lunar missions in the late 2020's

## Dev. & Advancement of Lunar Instrumentation (DALI)

- RFP for science and resource instruments

## Lunar Surface Instrument & Technology Payload (LSITP)

- RFP for CLPS payloads that address Strategic Knowledge Gaps, including ISRU for water and oxygen (solicitation is for payloads less than 15 kg)

## ISRU Next Space Technologies for Exploration Partnerships (NextSTEP)

- Request for Proposals for studies, and ISRU components and subsystems for water mining and $CO_2/H_2O$ Processing

## Announcement of Collaborative Opportunity (ACO)

- Space Act Agreement with NASA Centers

# NASA ISRU
# Lead-Make, Partner-Leverage, Eventually Buy

## Lead

- Resource characterization and prospecting (sufficient for NASA to rely on it)
- Technology risk reduction
- Moon/Mars ISRU capabilities for human mission needs (Initially)

## Partner & Leverage

- **Within NASA:** Technology and hardware development coordination
  - Modify existing technology developed to new needs/requirements
  - Select one lead and others buy copies (ex. PEM water electrolysis)
- **With Investment-based Terrestrial and Space Mining Companies**
  - External Capability Assessment Process (ECAP) Study identified areas of possible leverage for spin-in and spin-off technologies and approach
  - ISRU NextSTEP Broad Agency Announcement (BAA) first attempt to actively solicit terrestrial industry
  - Interest expressed in commercial production of propellants for NASA and space transportation companies (ULA propellant price point announcement in 2016)
  - Interest in technology partnerships expressed by Offworld and TransAstra on joint technology/capability development
  - Leave asteroid mining to Commercial Companies (TransAstra, DSI, Planetary Resources)
- **With Non-Market Space Companies** (SpaceX, Blue Origin)
  - Different partner/leverage and make/buy approach than with Investment-based companies
- **With International Space Agencies**
  - Determine strategic interests/technologies of importance with each potential partner
  - Must balance barter agreements with fostering commercial opportunities

## Possible NASA roles in ISRU Space Commercialization

- Characterize space resources, especially lunar polar water/volatiles
- Reduce technology/capability risk of ISRU hardware/equipment through in-house development and demonstration and SBIRs, BAAs, PPPs, Tipping Point, Challenges, etc.
- Initial anchor tenant for products

# Final Comment

**It's not about having the most efficient ISRU system to begin with.**

**It is about achieving the benefits of ISRU for a reasonable cost, mass, and risk.**

# Backup

# Why Implement Lunar ISRU?

Increasing investment and use of ISRU

## Lunar ISRU Can Sustain and Grow Human Lunar Surface Exploration

- **Lunar Resource Characterization for Science and Prospecting**
  - Provide ground-truth on physical, mineral, and volatile characteristics – provide geological context; test technologies to reduce risk for future extraction/mining
- **Mission Consumable Production:**
  - Propellants for reusable robotic landers and eventual use for crew and transportation; life support and fuel cell consumables to extend missions.
- **Learn to Use lunar resources and ISRU for Sustained Operations**
  - Civil Engineering and Construction: Site Preparation, Radiation protection, Landing Pads, etc.
  - Manufacturing with *In Situ* Derived Materials
  - Energy Generation, Storage, and Transfer: Thermal storage, Thermal Gradients, etc.

## Lunar ISRU Can Reduce the Risk and Prepare for Human Mars Exploration

- **Demonstrate ISRU to reduce the mass, cost, & risk of human Mars missions**
  - Propellant production from regolith (**10's MT/yr**); Produce, liquefy, store, transfer, & fuel ascent vehicle
  - Surface civil engineering and infrastructure emplacement for repeated landing at same location
- **Use Moon for operational experience and mission validation for Mars**
  - Pre-deploy, remote activation and operation, propellant transfer, landing with empty tanks
- **Enable new exploration capabilities with ISRU**
  - Refuelable hoppers, enhanced shielding, common mission fluids and depots

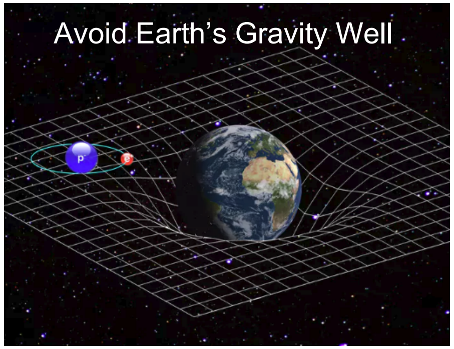
## Lunar ISRU Can Enable Economic Expansion into Space

- **Lunar Polar Water/Volatiles is Game Changing/Enabling**
- **Promote Commercial Operations/Business Opportunities**
  - Same as above but enhanced and accelerated
- **Support/promote establishment of reusable/commercial transportation**
  - Large scale polar ice mining (**100's MT/yr**)

# Leverage (Gear) Ratios using ISRU

**Every 1 kg of propellant made on the Moon or Mars saves 7.4 to 11.3 kg in LEO**

**Potential 334.5 mT launch mass saved in LEO = 3 to 5 SLS launches avoided per Mars Ascent**

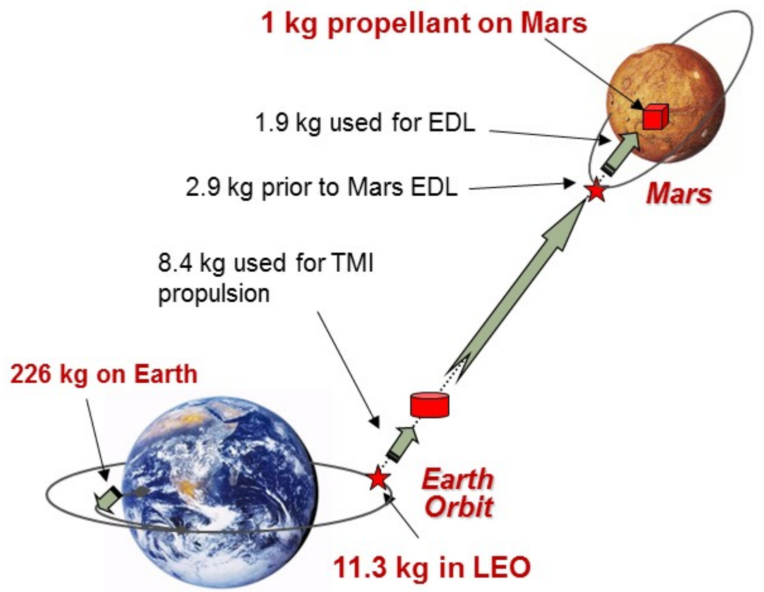



## Lunar missions

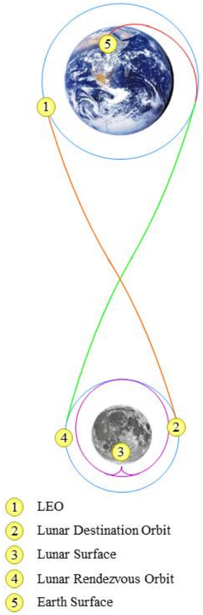
- Oxygen ($O_2$) only — 75%/80% of ascent propellant mass: 5 to 10 mT
- $O_2$/Hydrogen ($H_2$) — 100% propellant for single stage: 15 to 40 mT

## Mars missions

- Oxygen ($O_2$) only — 75% of ascent propellant mass: 20 to 23 mT
- $O_2$/Methane ($CH_4$) — 100% of ascent propellant mass: 25.7 to 29.6 mT; Regeneration of rover fuel cell reactant mass




Estimates based on Aerocapture at Mars




| A Kilogram of Mass Delivered Here… | …Adds This Much Initial Architecture Mass in LEO | …Adds This Much To the Launch Pad Mass |
|---|---|---|
| Ground to LEO | - | 20.4 kg |
| LEO to Lunar Orbit (#1→#2) | 4.3 kg | 87.7 kg |
| LEO to Lunar Surface (#1→#3; e.g., Descent Stage) | 7.5 kg | 153 kg |
| LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., Orion Crew Module) | 9.0 kg | 183.6 kg |
| Lunar Surface to Earth Surface (#3→#5; e.g., Lunar Sample) | 12.0 kg | 244.8 kg |
| LEO to Lunar Surface to Lunar Orbit (#1→#3→#4; e.g., Ascent Stage) | 14.7 kg | 300 kg |
| LEO to Lunar Surface to Earth Surface (#1→#3→#5; e.g., Crew) | 19.4 kg | 395.8 kg |

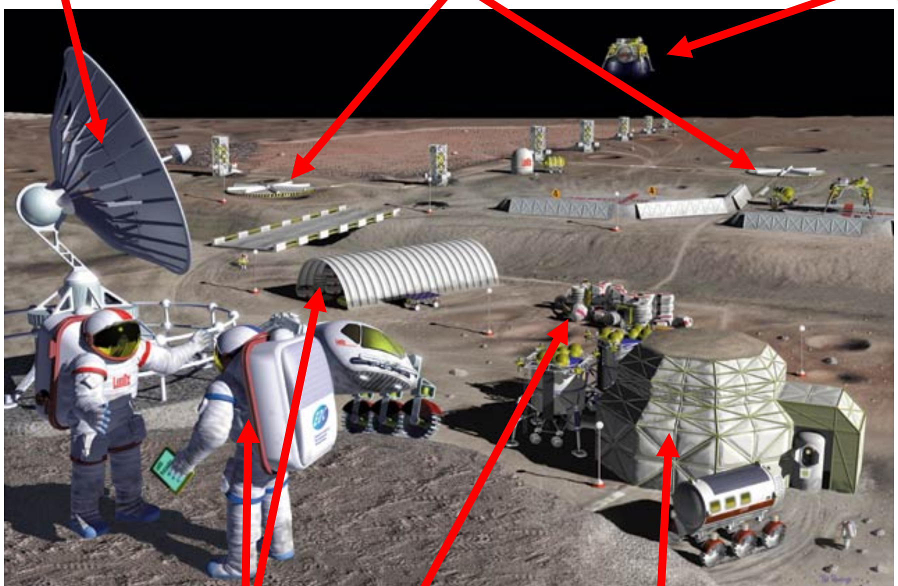
# ISRU is Similar to Establishing Remote Mining Infrastructure and Operations on Earth

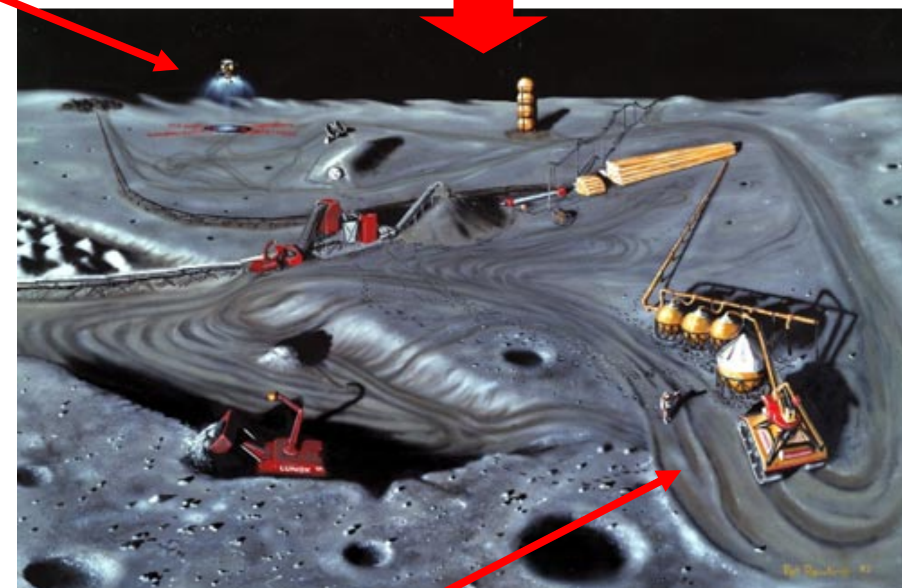
Communications
- To/From Site
- Local

Power:
- Generation
- Storage
- Distribution

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

Planned, Mapped, and Coordinated Mining Ops:
Areas for: i) Excavation, ii) Processing, and iii) Tailings

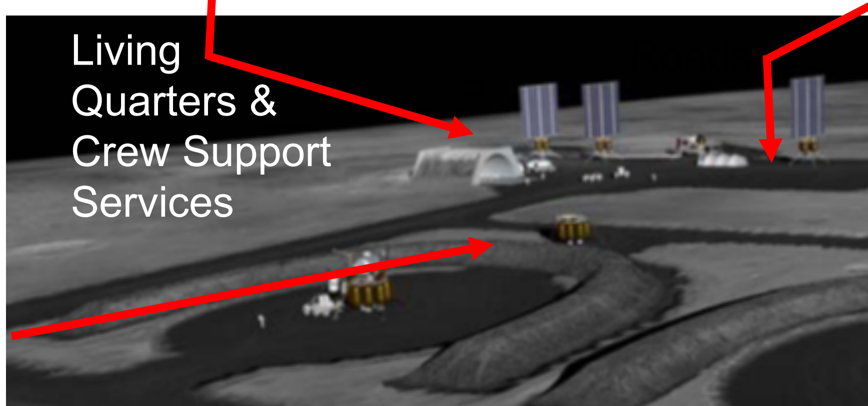




Maintenance & Repair

Logistics Management

Construction and Emplacement



Living Quarters & Crew Support Services

# Utilize SKGs and Commercial interests as drivers for ISRU Demos and Pilot Plants

## Strategic Knowledge Gaps (SKGs) for Moon & Mars

### Lunar Strategic Knowledge Gaps

| ISRU | Lunar Strategic Knowledge Gaps |
|---|---|
| | **I. Understand the lunar resource potential.** |
| | A. Solar Resources |
| | B. Regolith Resources 1 (Earth testing) |
| ★ | C. Regolith Resources 2: Volatiles in mare and highland regolith |
| ★ | D. Polar Resources |
| | Geotechnical charactgeristics of cold traps |
| | Physiography and accessibility of cold traps |
| | Charging and plasma environment characterization |
| | Water/volatile characterization 1 to 2 meters deep |
| | Water/volatile characterization over 10's of meters |
| | Mineralogical, elemental, molecular, and isotopic make up of volatiles |
| | Physical nature of volatiles |
| | Spatial and temporal distribution of surface OH/H2O |
| | Measure exospheric water and monitor movement towards PSRs |
| ★ | E. Pyroclastic Deposit Resources |
| | F. Lunar ISRU production efficiency 1 (Earth testing) |
| ★ | G. Lunar ISRU production efficiency 2 |
| | **II. Understand the lunar environment and its effects on human life.** |
| | A. Solar Activity (Earth based) |
| | B. Radiation at the lunar surface |
| | Radiation environment on the surface 2 |
| | Radiation shielding effect of lunar materials 2 |
| | C. Biological impact of dust |
| | D. Maintaining peak human health |
| | **III. Understand how to work and live on the lunar surface.** |
| ★ | A. Resource Production |
| | Technology for excavation of lunar resources |
| | Technologies for transporting lunar resources |
| | Technologies for comminution of lunar resources |
| | Technologies for beneficiating lunar resources |
| ☆ | B. Geodetic Grid and Navigation |
| | Lunar topography data |
| | Autonomous surface navigation |
| ☆ | C. Surface Trafficability |
| | D. Dust and Blast Ejecta |
| ☆ | Lunar dust remediation |
| | Regolith adhesion and associated mechanical degradation |
| ☆ | Descent/ascent engine blast ejecta |
| | E. Plasma environment and charging |
| ☆ | F. Energy production and storage |
| | Energy production and storage - non polar missions |
| | Energy production and storage - polar missions |
| | Propellant scavenging |
| ☆ | G. Radiation shielding |
| ☆ | H. Micrometeroite shielding |
| | I. Lunar mass contribution/distribution |
| | J. Habitat, life support and mobility |

### Mars Strategic Knowledge Gaps

| ISRU | Mars Strategic Knowledge Gaps |
|---|---|
| | **Atmospheric SKGs** |
| | A1-1 Global Temperature Field |
| | A1-2 Global Aerosol Profiles and Properties |
| | A1-3 Global Winds and Wind Profiles |
| | A2-1 Atmospheric Modeling |
| | A4-3 Aerocapture Demo |
| | B1-1 Dust Climatology |
| | B1-2 Global Surface Pressure: Local Weather |
| | B1-3 Surface Winds |
| | B1-4 EDL Profiles |
| | B1-5 Atmospheric Electricity Conditions |
| | B1-6 EDL Technology Demo |
| ☆ | B1-7 Ascent Technology Demo |
| | **Mars Surface and ISRU** |
| ☆ | B6-1 Dust Physical, Chemical and Electrical Properties |
| | B6-2 Dust Column Abundances |
| ☆ | B6-3 Trace Gas Abundances |
| ★ | B7-1 Regolith Physical Properties and Structure |
| ☆ | B7-4 Auto Rover Tech Demo |
| ★ | B7-6 Sample Handling Tech Demo |
| ☆ | B8-1 Fission Power Tech Demo |
| ☆ | D1-1 Cryo Storage Demo |
| ★ | D1-2 Water ISRU Demo |
| ★ | D1-3 Hydrated Mineral Compositions |
| ★ | D1-4 Hydrated Mineral Occurrences |
| ★ | D1.5 Shallow Water Ice Composition and Properties |
| ★ | D1-6 Shallow Water Ice Occurrences |
| | **Mars Surface Hazards** |
| | B4-1 Electricity |
| ★ | B4-2 Dust Physical, Chemical, and Electrical Properties |
| ★ | B4-3 Regolith Physical Properties and Structure |
| ☆ | B7-2 Landing Site Selection |
| ☆ | B7-3 Trafficability |
| ☆ | B7-5 Environmental Exposure Tech Demo |
| | **Phobos/Deimos** |
| | A3-1 Orbital Particulate Environment |
| | A4-1 Autonomous Redezvous and Docking |
| | C1-1 Surface Composition |
| | C2-1 Electrostatic and Plasma Environments |
| | C2-2 Gravitational Field |
| | C2-3 Regolith Properties |
| | C2-4 Thermal Environment |
| | C3-1 Anchoring and Surface Mobility Systems - Tech Demo |
| | **Planetary Protection** |
| | B2-1 Biohazards |
| ★ | B5-1 Identify and Map Special Regions |
| | B5-2 Model Induced Special Regions |
| | B5-3 Microbial Survival, Mars Conditions |
| | B5-4 Develop Contanminant Dispersal Model |
| ☆ | B5-5 Forward Contamination Tech Demo |
| | C2-4 Thermal Environment |

★ = Directly Relevant to ISRU
☆ = Strongly Influences ISRU

# Lunar Polar Volatiles*
## (Observed at LCROSS Site)

| | | | | | LCROSS | | LRO | Chand-1 |
|---|---|---|---|---|---|---|---|---|
| | Column Density (# $m^{-2}$) | Relative to H2O(g) (NIR spec only) | Concentration (%wt)* | Long-term Vacuum Stability Temp (K) | UV/Vis | NIR | LAMP | M3 |
| $H_2O$ | 5.1(1.4)E19 | 1 | 5.5 | 106 | | x | | |
| CO | 2.2e12±1.5e11 | | 0.70 | 15 | | | x | |
| $H_2$ | 5.8e13±1.0e11 | | 1.40 | 10 | | | x | |
| $H_2S$ | 8.5(0.9)E18 | 0.1675 | 1.74 | 47 | x | x | | |
| Ca | 3.3e12±1.3e10 | | 0.20 | 412 | | | x | |
| Hg | 5.0e11±2.9e8 | | 0.24 | 135 | | | x | |
| $NH_3$ | 3.1(1.5)E18 | 0.0603 | 0.31 | 63 | | x | | |
| Mg | 9.0e10±5.3e9 | | 0.40 | 346 | | | x | |
| $SO_2$ | 1.6(0.4)E18 | 0.0319 | 0.64 | 58 | | x | | |
| $C_2H_4$ | 1.6(1.7)E18 | 0.0312 | 0.27 | 50 | | x | | |
| $CO_2$ | 1.1(1.0)E18 | 0.0217 | 0.32 | 50 | x | x | | |
| $CH_3OH$ | 7.8(42)E17 | 0.0155 | 0.15 | 86 | | x | | |
| $CH_4$ | 3.3(3.0)E17 | 0.0065 | 0.03 | 19 | | x | | |
| OH | 1.7(0.4)E16 | 0.0003 | 0.00 | 278 | x | x | | x |
| $H_2O$ (adsorb) | | | 0.001-0.002 | 323 | | | | x |
| Na | | 1-2 kg | | 197 | x | | | |
| CS | | | | | x | | | |
| CN | | | | | x | | | |
| NHCN | | | | | x | | | |
| NH | | | | | x | | | |
| $NH_2$ | | | | | x | | | |

**Besides $H_2O$ and $H_2$, there are other volatiles of interest as well including CO, $CO_2$, and hydrocarbons**

*Table courtesy of Tony Colaprete

# Regolith vs Polar Water/Volatiles: Pros & Cons

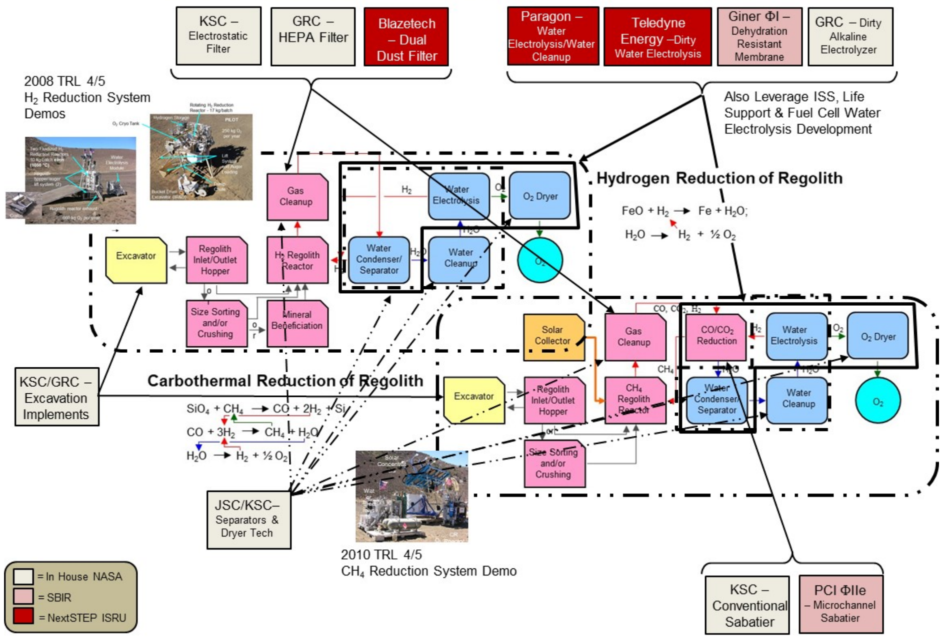
| | $O_2$ Extraction | | | | Polar $H_2O$ | |
|---|---|---|---|---|---|---|
| | $H_2$ Reduction | $CH_4$ Reduction | Molten Oxide Electrolysis | Ionic Liquid Reduction | PVEx | Dome |
| **Resource Knowledge** | Good - Orbital High Resolution & Apollo Samples | | | | Poor - Orbital Low Resolution - LCROSS Impact | |
| **Site Specificity** | Moderate (Ilminite & Pyroclastic Glasses Preferred) | Low to Moderate (Iron oxides and Silicates_ | | | High (Permanently Shadowed Crater/Regions Near extensive sunlight) | |
| **Temperature to Extract** | Moderate (900 C) | High (>1600 C) | High (>1600 C) | Low (100+ C) | Low (<150 C) | |
| **Energy per Kilogram** | High | Moderate | Moderate | ? | Low ? | |
| **Extraction Efficiency wt%*** | 1 to 5 | 10 to 15 | 20 to 40 | ? | Dependant on water concentration | |
| **TRL** | 4-5 | 4-5 | 2-3 | 2 | 3 | 1-2 |

*kg $O_2$/kg bulk regolith

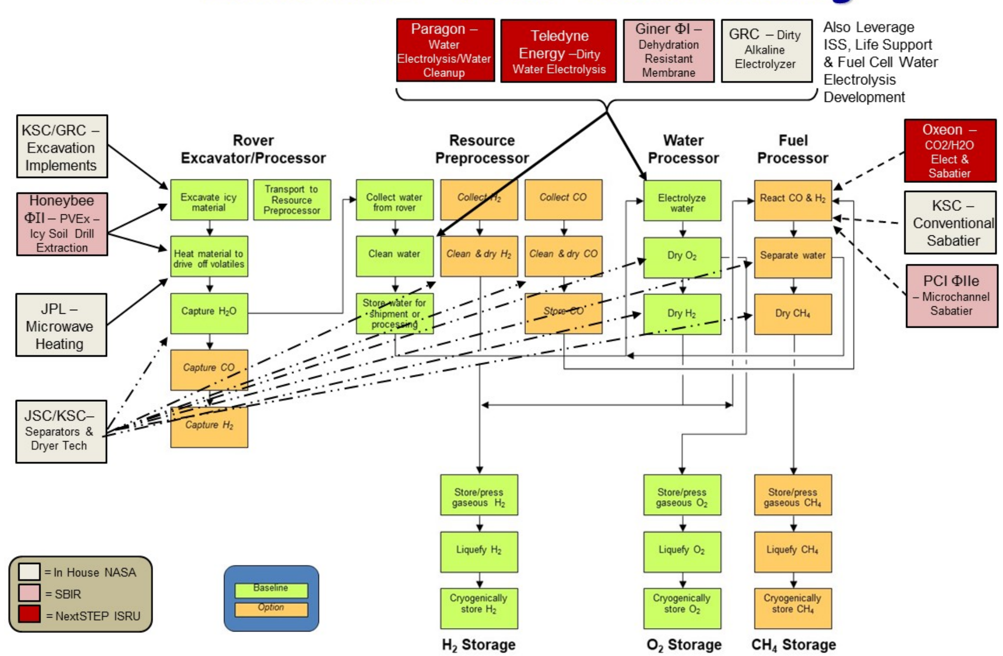
- **Oxygen Extraction from Regolith**
  - $H_2$ Reduction Lowest Efficiency/Lowest Risk due to <900 C and granular
  - Molten Oxide Electrolysis is Highest Efficiency/Highest Risk due to high temperature/molten material and electrode degradation
  - $CH_4$ Reduction Moderate Efficiency/Moderate Risk but is highly dependent on solar concentrator mass and performance
  - Ionic liquid reduction is promising but further research is required
- **Polar Water/Volatile Extraction**
  - Not much energy required to release water/volatiles
  - Excavation/extraction highly dependent on concentration, depth, and homogeneity of water resource
  - Low temperatures (40 to 100 K) increases energy and material selection concerns

# Need to Consider Applicability of Mars ISRU Work toward Lunar ISRU

## Lunar ISRU – Mineral Processing for $O_2$




## Lunar ISRU – Polar Volatile Mining



# Lunar Resources & Products of Interest

## LUNAR RESOURCES

### MARE REGOLITH

Ilmenite - 15%

| | |
|---|---|
| FeO•$TiO_2$ | 98.5% |

Pyroxene - 50%

| | |
|---|---|
| CaO•$SiO_2$ | 36.7% |
| MgO•$SiO_2$ | 29.2% |
| FeO•$SiO_2$ | 17.6% |
| $Al_2O_3$•$SiO_2$ | 9.6% |
| $TiO_2$•$SiO_2$ | 6.9% |

Olivine - 15%

| | |
|---|---|
| 2MgO•$SiO_2$ | 56.6% |
| 2FeO•$SiO_2$ | 42.7% |

Anorthite - 20%

| | |
|---|---|
| CaO•$Al_2O_3$•$SiO_2$ | 97.7% |

### VOLATILES (Solar Wind & Polar Ice/$H_2$)

| | |
|---|---|
| Hydrogen ($H_2$) | 50 - 150 ppm |
| Helium (He) | 3 - 50 ppm |
| Helium-3 ($^3$He) | $10^{-2}$ ppm |
| Carbon (C) | 100 - 150 ppm |
| Polar Water ($H_2O$)/$H_2$ | 1 - 10% |

→ Thermal Volatile Extraction

## Hydrogen Reduction of Ilmenite/glass Process

$2FeTiO_3 + 2H_2 \xrightarrow{900°C} 2H_2O + 2Fe + 2TiO_2$ → 2Fe

Water electrolysis

$O_2 + 2H_2 \xleftarrow{25°C} 2H_2O$ → $O_2$

## Sulfuric Acid Reduction

Desolve/Digest Reactor

$2FeTiO_3 + 2H_2SO_4 \rightarrow 2H_2O + 2FeSO_4 + 2TiO_2$

Electrolysis bed

$O_2 + 2Fe + 2H_2SO_4 \leftarrow 2H_2O + 2FeSO_4$ → $O_2$, 2Fe

## *New: Ionic Liquids*

$M_nO_m + 2_m[H^+] \rightarrow mH_2O + nM^{+m}$

## Methane Reduction (Carbothermal) Process

Methane Reduction Furnace

$2FeTiO_3$, $Fe_2SiO_4$, $Fe SiO_3$, $Mg_2SiO_4$, $MgSiO$, $CaSiO_3$ $+ 2CH_4 \xrightarrow{1625°C} 2CO + 4H_2 +$

- $2TiO_2 + 2Fe$ → 2Fe
- $2FeO + Si$
- $FeO + Si$
- $2MgO + Si$
- $MgO + Si$
- $CaO + Si$

→ Si

Methane Reformer

$2H_2O + 2CH_4 \xleftarrow{250°C} 2CO + 6H_2$

Water electrolysis

$2H_2O \xrightarrow{25°C} 2H_2 + O_2$ → $O_2$

## Molten Electrolysis

Molten Electrolysis Reactor

- $2SiO_2 \rightarrow 2SiO + O_2$ → $O_2$
- $2FeTiO_3 \rightarrow 2Fe + 2TiO_2 + O_2$
- $2FeO \rightarrow 2Fe + O_2$

→ $O_2$, 2Fe

## Vapor Pyrolysis Process

Pyrolysis Reactor/Condenser

- $2SiO_2 \xrightarrow{>2000°C} 2SiO + O_2$ → $O_2$
- $2FeTiO_3 \xrightarrow{2500°C} 2Fe + 2TiO_2 + O_2$
- $2FeO \xrightarrow{>2000°C} 2Fe + O_2$

→ $O_2$, 2Fe

- $2Al_2O_3 \xrightarrow{>2000°C} 4AlO + O_2$ → $O_2$
- $2Al_2O_3 \xrightarrow{>2000°C} 2AlO + 2Al + O_2$ → $O_2$, 2Al
- $2MgO \xrightarrow{>2000°C} 2Mg + O_2$
- $2CaO \xrightarrow{>2000°C} 2Ca + O_2$

→ $O_2$

- $2CaAl_2Si_2O_8 \xrightarrow{2500°C} 2Ca + 4AlO + 4SiO + 4O_2$ → $4O_2$, 2Ca
- $2CaAl_2Si_2O_8 \xrightarrow{2500°C} 2Ca + 2AlO + 2Al + 4SiO + 5O_2$ → $5O_2$, 2Al, 2Ca

# The Chemistry of Mars ISRU

## Oxygen ($O_2$) Production Only

**Zirconia Solid Oxide $CO_2$ Electrolysis (SOE)**
$2\,CO_2 \xrightarrow{900-1000\,C} 2\,CO + O_2$ [Pt catalyst] → $O_2$

**Reverse Water Gas Shift (RWGS)**
$CO_2 + H_2 \underset{}{\overset{400-650\,C}{\rightleftharpoons}} CO + H_2O$ [catalyst] → $H_2O$ → WE to $O_2$

**Bosch**
$CO_2 + 2\,H_2 \xrightarrow{450-600\,C} C + 2\,H_2O$ [Ni, Ru, Fe, or Co catalyst] → $H_2O$ → WE to $O_2$

## Oxygen ($O_2$) & Methane ($CH_4$) Production

**Sabatier Catalytic Reactor (SR)**
$CO_2 + 4\,H_2 \overset{200-300\,C}{\rightleftharpoons} CH_4 + 2\,H_2O$ [Ru catalyst] → $H_2O$, $CH_4$ → WE to $O_2$

**Methane Reformer**
$CO + 3\,H_2 \xrightarrow{250\,C} CH_4 + H_2O$ [Ni catalyst] → $H_2O$, $CH_4$ → WE to $O_2$

**Electrochemical Reduction**
$CO_2 + 2\,H_2O \rightarrow CH_4 + 2\,O_2$ [Anode/Cathode] → $O_2$, $CH_4$

## Other Hydrocarbon Fuel Production

**Fischer-Tropsch (FT)**
$n\,CO + (2n+1)\,H_2 \xrightarrow{>150\,C} C_nH_{2n+2} + n\,H_2O$ [catalyst] → $H_2O$, $C_nH_{2n+2}$ → WE to $O_2$

**Methanol**
$CO + 2\,H_2 \xrightarrow[50-100\,atm]{250\,C} CH_3OH$ [ZnO catalyst] → $CH_3OH$
$CO_2 + 3\,H_2 \rightarrow CH_3OH + H_2O$ → $H_2O$, $CH_3OH$ → WE to $O_2$

## Oxygen ($O_2$) &/or Hydrogen ($H_2$) Production

**Water Electrolysis (WE)**
$2\,H_2O \rightarrow 2\,H_2 + O_2$ → $O_2$, $2\,H_2$

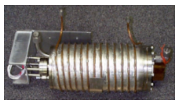
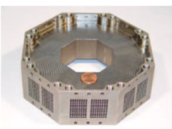
**Steam Reforming**
$H_2O + CH_4 \rightarrow 3\,H_2 + CO$ → $3\,H_2$

**Dry Reforming**
$CO_2 + CH_4 \rightarrow 2\,H_2 + 2\,CO$ → $2\,H_2$

**$2^{nd}$ Step**

# Mars ISRU Technology, System, & Flight Development in the 1990's

**Development Aimed at Supporting Mars Sample Return with ISRU in 2005/7**


## $CO_2$ Collection & Separation

- Mars atmosphere adsorption pump (JPL, ARC, LMA, JSC)
- Microchannel adsorption pump (PNNL)
- Mars atmosphere solidification pump (LMA, SBIR, NASA)

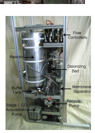
## $CO_2$ Processing

- $CO_2$ electrolysis & low pressure dissociation (NASA, Univ., Industry, SBIRs)
- Reverse Water Gas Shift (KSC, PNNL, SBIRs)
- Sabatier reactors (NASA, Industry, SBIRs)
- Methane reformer (JPL, SBIRs)
- Hydrocarbon fuel reactors - methanol, toluene, ethylene, etc. (SBIRs)
- Microchannel reactors/heat exchangers (PNNL, SBIRs)

## Water Processing

- Water electrolysis/decomposition (NASA, Industry, SBIRs)





## Systems

- 1st Gen Sabatier/Water Electrolysis (SWE) breadboard under ambient & Mars environment testing (NASA, Pioneer Astronautics)
- 1st Generation Reverse Water Gas Shift with and w/o Fuel production (NASA, Pioneer Astronautics)

## Flight Demonstrations

- Mars ISPP Precursor (MIP) – Mars 2001 (Flight unit built & tested)
  - $5 \times 10^{-4}$ kg/hr $O_2$; 15 W; 10 operations
- PROMISE – Mars 2003 (Awarded but cancelled)
  - $8.7 \times 10^{-4}$ kg/hr $O_2$ (with $CH_4$ production); 30 W; 90 sols