EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

NASA Plans for In Situ Resource Utilization (ISRU) Development, Demonstration, and Implementation

Presentation to COSPAR, July 14, 2022

Gerald Sanders | ISRU System Capability Lead | NASA JSC, Houston, TX, gerald.b.sanders@nasa.gov
Julie Kleinhenz | ISRU System Capability Deputy | NASA GRC, Cleveland, OH, julie.e.Kkeinhenz@nasa.gov
Diane Linne | ISRU Subject Matter Expert| NASA GRC, Cleveland, OH, diane.l.linne@nasa.gov

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


PRESIDENTIAL MEMORANDA

Presidential Memorandum on Reinvigorating America's Human Space Exploration Program

INFRASTRUCTURE & TECHNOLOGY | Issued on: December 11, 2017

"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 to bring back to Earth new knowledge and opportunities. Beginning with mission 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

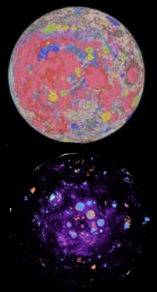
"Space activities benefit humanity. They power the global economy; underpin U.S., allied, and partner national security; improve the daily lives of Americans and people around the world; and inspire us to pursue our dreams. We are on the cusp of historic changes in access to and use of space – changes that have the potential to bring the benefits of space to more people and communities than ever before. The United States will harness the use of space to tackle the most pressing challenges at home and abroad, while leading the international community in preserving the benefits of space for current and future generations."

United States Space Priorities Framework

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

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

Commercial Scale Water, Oxygen, Metals & Commodity Production



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

Commodities for Habitats & Food Production

- Water, fertilizers, carbon dioxide, and other crop growth support
- Crop production habitats and processing systems
- Consumables for life support , EVAs, and crew rovers/habitats for growing human space activities

In Situ Derived Feedstock for Construction, Manufacturing, & Energy

- Initial goal of simple landing pads and protective structures
- 100's to 1000's metric tons of regolith-based feedstock for construction projects
- 10's to 100's metric tons of metals, plastics, and binders
- Elements and materials for multi-megawatts of energy generation and storage
- Recycle, repurpose, and reuse manufacturing and construction materials & waste

Commodities for Commercial Reusable In-Space and Surface Transportation and Depots

- Initially 30 to 60 metric tons per lander mission
- 100's to 1000's metric tons per year of for Cis-lunar Space
- 100's metric tons per year for human Mars transportation

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

*Commodities are items and consumables that can be eventually sold

NASA Lunar ISRU Objectives

Lunar ISRU To Sustain and Grow Human Lunar Surface Exploration

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

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

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

Lunar ISRU To Enable Economic Expansion into Space

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

Lunar Resources and Commodities

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

Resources

Lunar Regolith

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

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

Polar Water/Volatiles

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

Initial Commodities

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

Refined Products

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

Gold/Bold text = most important initial commodities

Plan to Achieve ISRU Outcome

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

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

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

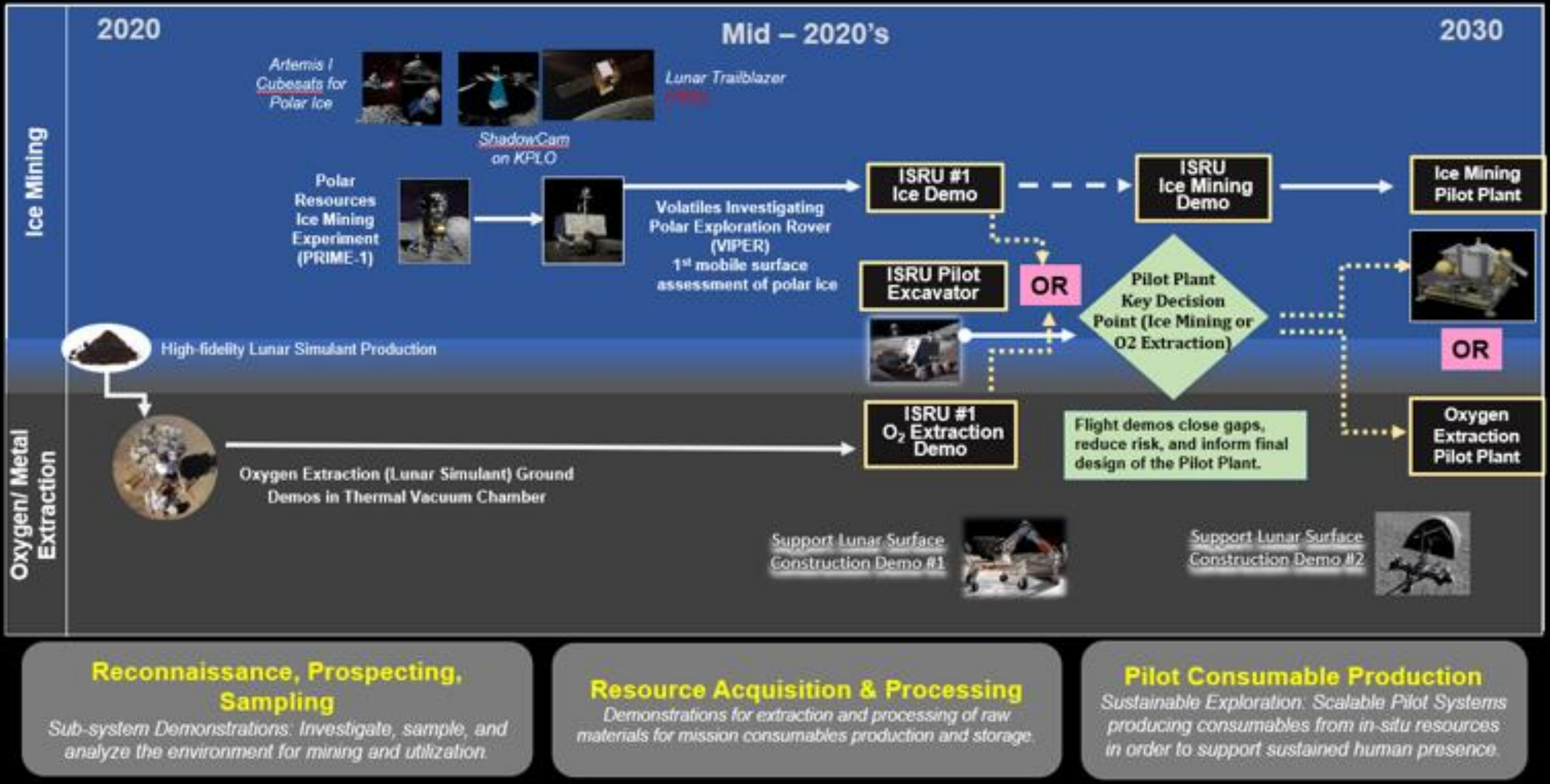
- **Reduce Risk of ISRU for Human Exploration & Space Commercialization thru CLPS Missions**
  - Understand lunar polar resources for technology development, site selection, mission planning
  - Obtain critical data (ex. regolith properties, validate feasibility of ISRU processes)
  - Demonstrate critical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

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

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

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

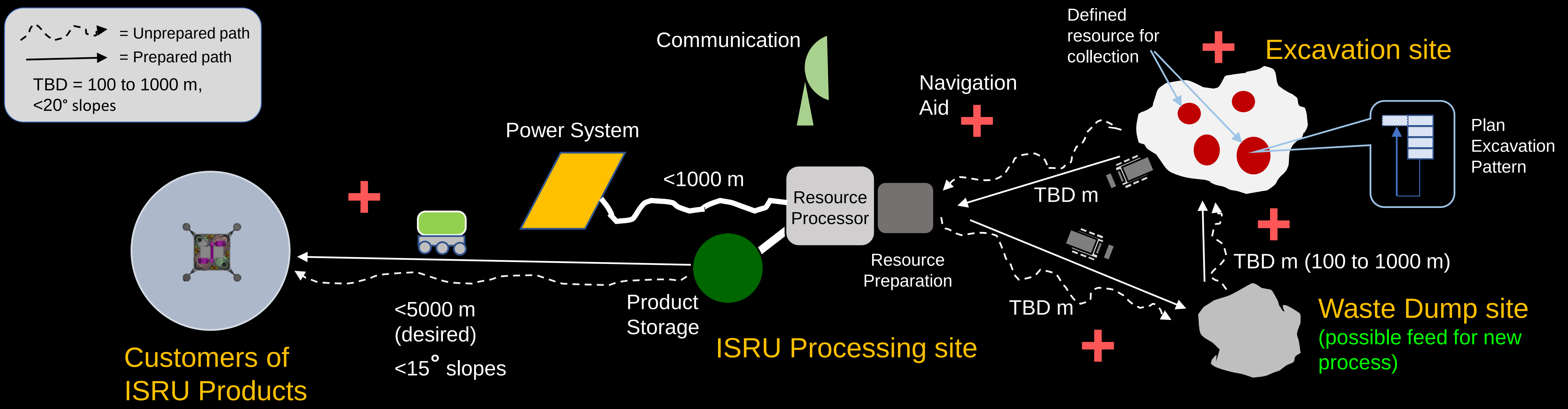
ISRU Dual Path to Full Implementation & Commercialization



Full-scale implementation & Commercial Operations

- Dual Path that includes both Water Mining and Oxygen/Metal from Regolith
  - O_2/Metal Path supports Surface Construction as well
- Ground development of multiple critical technologies in both pathways underway to maximize success and industry involvement
- Resource assessment missions to obtain critical data on mineral and water/volatile resources have started
  - PRIME-1 validates critical VIPER instruments and lunar highland material properties (for subsequent ground development)
- Demonstrations are aimed at reducing the risk of Pilot Plant design and operation (and subsequent Full-scale implementation)
  - Pilot Plant demonstrates performance, end-to-end operations, and quality of product for implementation and use

Lunar ISRU System and Concept of Operations



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

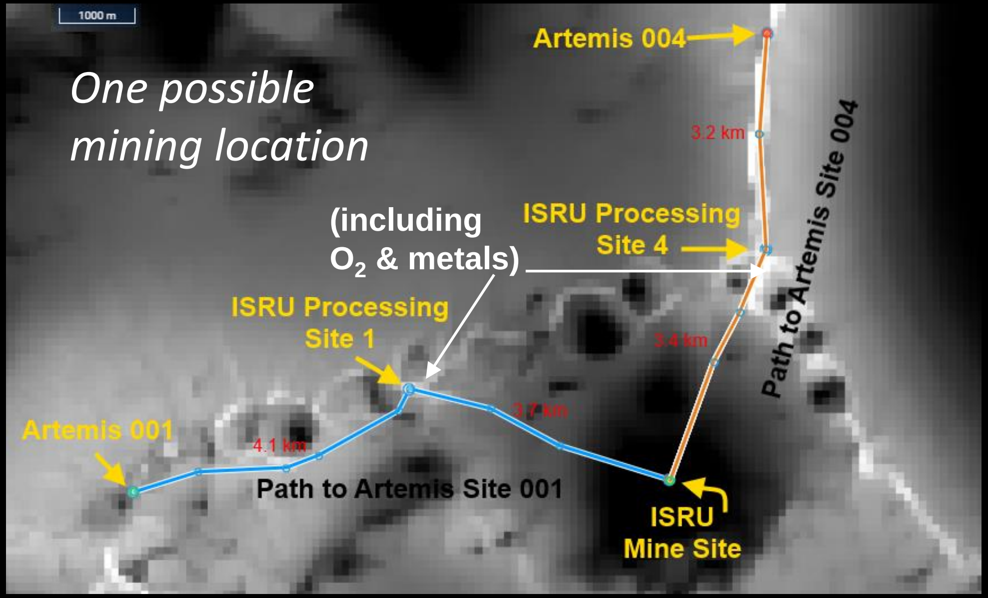
ISRU Mining & Processing Site Selection Criteria

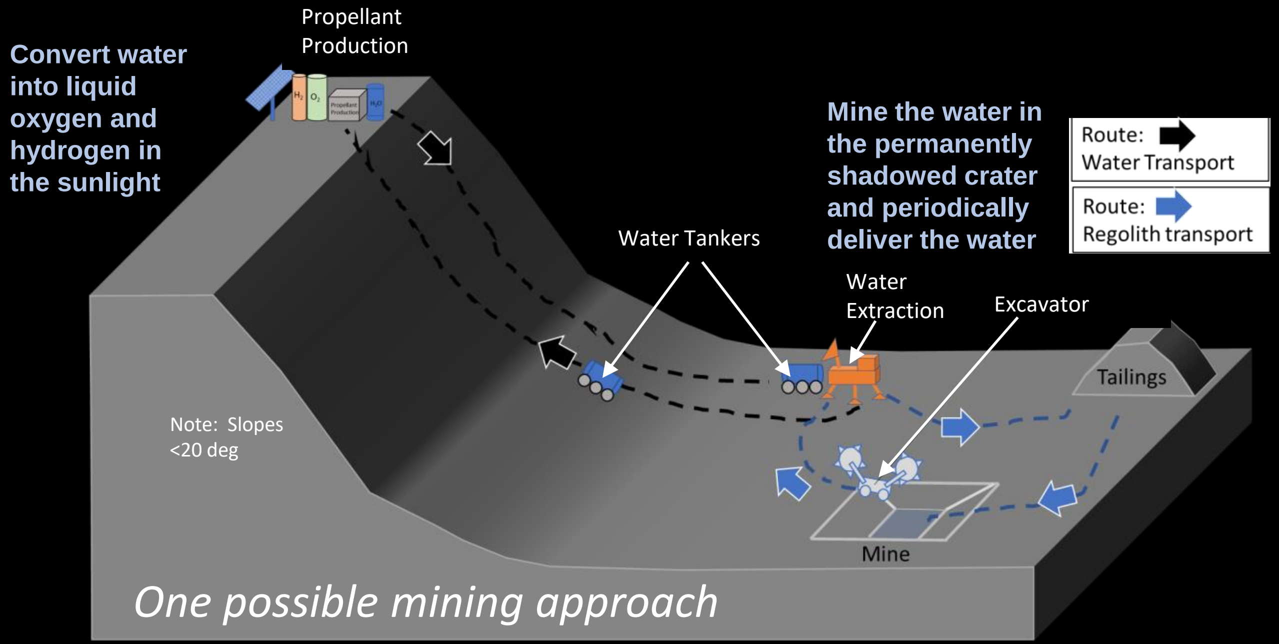
- **Sustained Communications**
  - Direct communication with Earth

  and/or
  - Communication satellites and surface relays

- **Sustained Sunlit Region Near Resources:**
  - Sustained sunlight (>220 days with long periods of continuous sun)
  - Power in or directed into shadowed resource location (<5 km desired)

- **Assessable Resources**
  - Mining location relatively flat with minimal boulders/rock distributions
  - Traversable path from mining location to water processing location: <20 Deg slopes, <5 km desired





- **Location near Sustained Human Outpost/Customers**
  - Traversable path between ISRU Processing/storage and Outpost/ Landing pads
  - Crew/robotics for offloading, setup, & periodic maintenance

- **Predicted/Confirmed Resources**
  - Ice Stability Region (ISR): Sustained temperatures below 100 K (ice stability)
  - Prediction of ice depth at <1m with an anticipated lateral distribution sufficient to meet ISRU tonnage requirements (neutron, thermal, & spectroscopic data)

9

Initial ISRU Mission Study Ground Rules and Assumptions

Oxygen Mining

- Produce 10 metric tons of O_2 per year (225 days of operation)
- Each ISRU module (3) produces 15.6 kg of O_2 per day (3500 mt O_2 per year per module)
  - Carbothermal Reduction process and Polaris excavator
- ISRU plant, excavation zone, and dump zone form triangle with 100 m each leg
- Excavators
  - 2 utilized for redundancy
  - Batteries charged every 4.5 days (1 kWhr discharged maximum 80% - 50 charge cycles per operating year)
  - Operate via tele-operation/supervised-autonomy with a communication link through the lander to Gateway to Earth
- Oxygen is liquefied and stored in the descent stage LO_2 tank
- Attempt to fit on single lander with 3.6 mT payload capability
  - Only 2 of 3 modules could be accommodated in mass; packaging not an issue

“Lunar Production System for Extracting Oxygen from Regolith”, ASCE Earth & Space, 4/2021
J. Aerosp. Eng., 2021, 34(4): 04021043

Water Mining

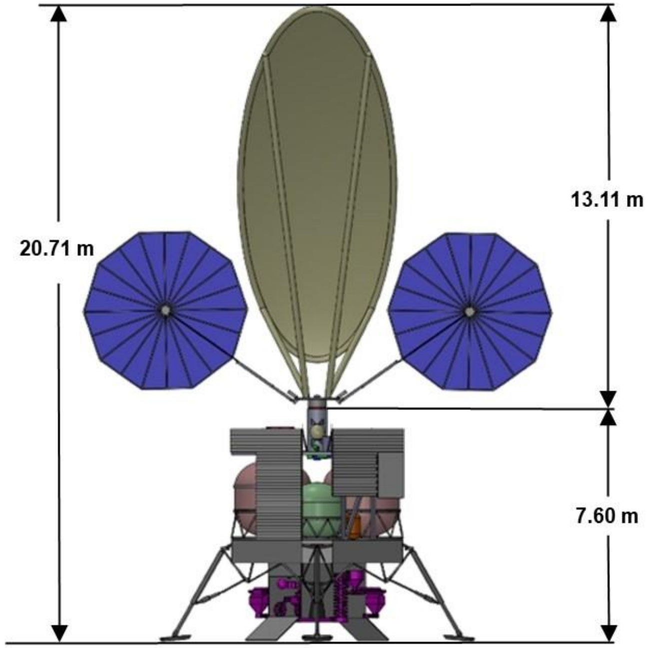
- Produce 15 metric tons of H_2O per year(based 225 days of operation and on 6:1 propulsion O_2/H_2 ratio vs 8:1 for water)
  - Lunar auger dryer and RASSOR excavator
- Power systems are NOT included in mass.
  - The power needs are stated, but a power mass is not included in this study.
- Packing of all full-scale modules is not addressed.
- Communication and command/control systems are not explicitly addressed
- Mobility subsystems include estimates for mass & power load
- Margins held at subsystem level
- Oxygen and hydrogen are liquefied and stored in cryogenic tanks
- System level thermal management systems are not included

Baseline Case Key Inputs	
Water concentration	5%
Production requirement	10 mT O_2
Actual production	13 mT O_2 1.7 mT H_2
Water required	15 mT water
Regolith required (75% extraction efficiency)	398 mT
Mine size at 30cm depth	32m x 32m
Time to water transport	10 days

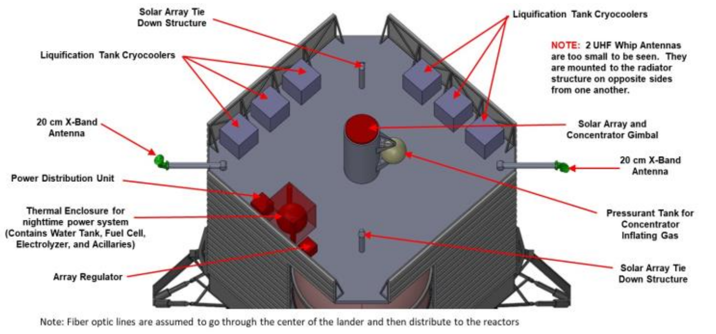
“Case Study for Lunar ISRU Systems Utilizing Polar Water”, AIAA ASCEND, 16-18 Nov., 2020

Mission Study Concepts

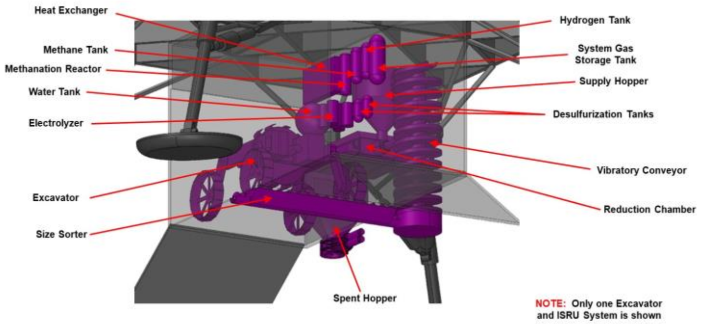
Oxygen from Regolith Mining



Upper Lander Packaging



Lower Lander Packaging

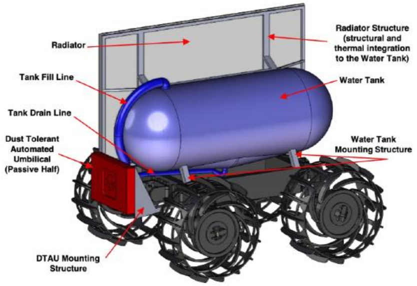


Polaris Excavator

“Lunar Production System for Extracting Oxygen from Regolith”, ASCE Earth & Space, 4/2021
J. Aerosp. Eng., 2021, 34(4): 04021043

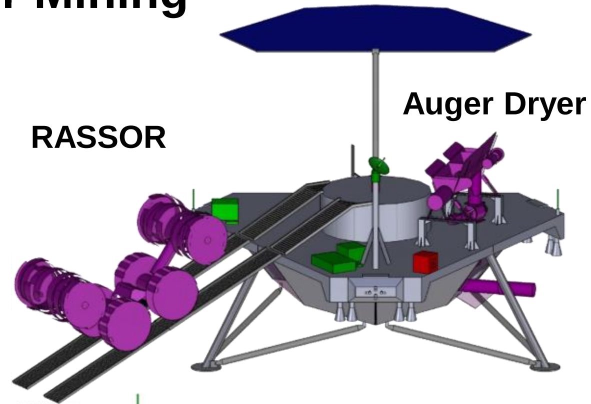
Polar Water Mining

Water Tanker

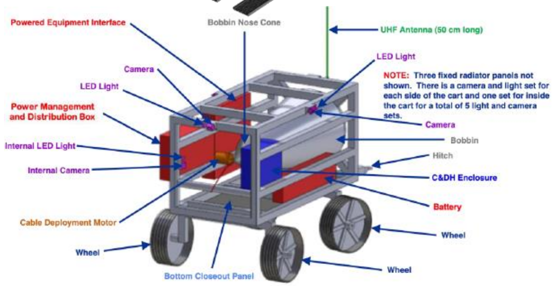


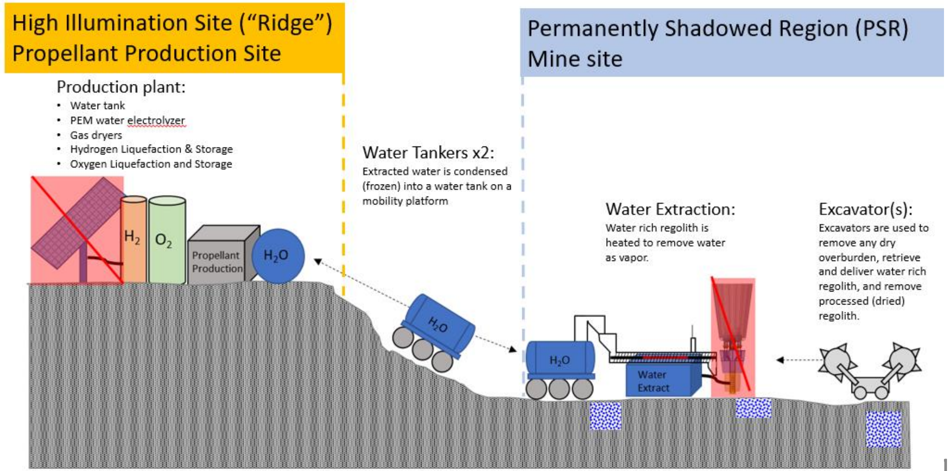
RASSOR

Auger Dryer



Power Cable Cart





“Lunar Water Pilot Plant Conceptual Design”, AIAA ASCEND, 16-18 Nov., 2020

Oxygen from Regolith Plant Mass and Power Estimates*

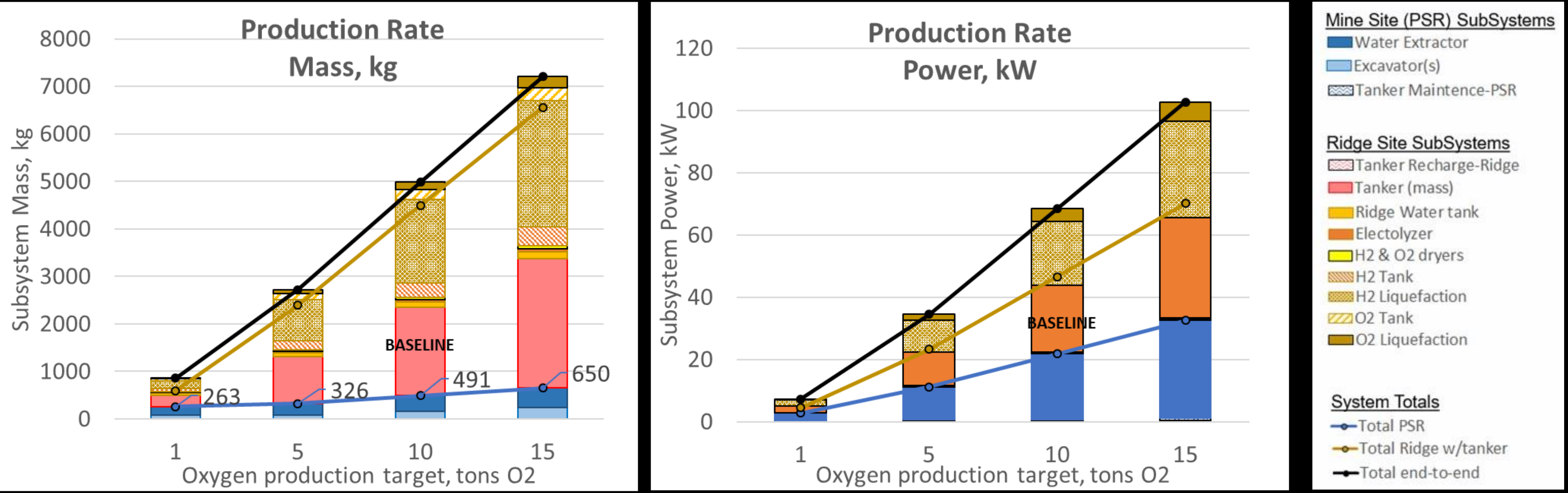
	1 t O2 per year		3.5 t O2 per year		7 t O2 per year		10.5 t O2 per year	
	Mass	Operating Power	Mass	Operating Power	Mass	Operating Power	Mass	Operating Power
	Total (kg)	Total (W)	Total (kg)	Total (W)	Total (kg)	Total (W)	Total (kg)	Total (W)
Oxygen Production Plant	**946**	**2831**	**1679**	**7307**	**3459**	**15166**	**4142**	**21510**
Supporting Systems	493	273	916	619	1926	1221	2109	1607
Command & Data Handling	8	14	8	14	8	14	8	14
Communications & Tracking	55	111	55	111	55	111	55	111
Elect. Power Generation, Dist, & Mgt.	48	148	79	494	124	1096	166	1482
Energy Storage	48		111		328		332	
Thermal Control (includes concentrator)	101		229		451		585	
Payload Deck	36		130		386		389	
Structures & Mechanisms	196		304		575		575	
ISRU System	453	2558	763	6688	1533	13945	2033	19903
O2 Production	246	2015	334	5170	676	10504	926	15360
O2 Storage* and Transfer	20	5	40	5	79	5	79	5
Excavator Subsystem	105		138		276		276	
Command & Data Handling	12	50	12	50	23	101	35	151
Liquefaction	20	488	66	1463	131	3335	198	4388
Thermal Control	50		173		347		520	

Pilot Scale

Initial Full Scale

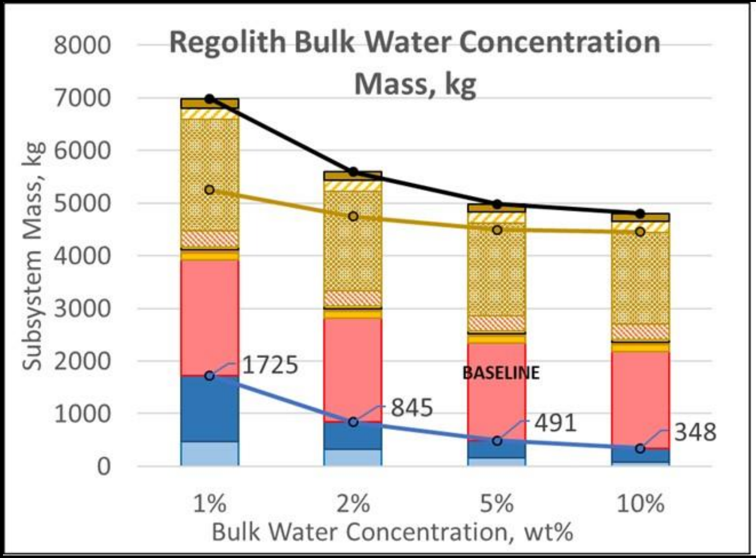
"*Results scaled by Diane Linne from COMPASS study presented in "Lunar Production System for Extracting Oxygen from Regolith", ASCE Earth & Space, 4/2021, Aerosp. Eng., 2021, 34(4): 04021043

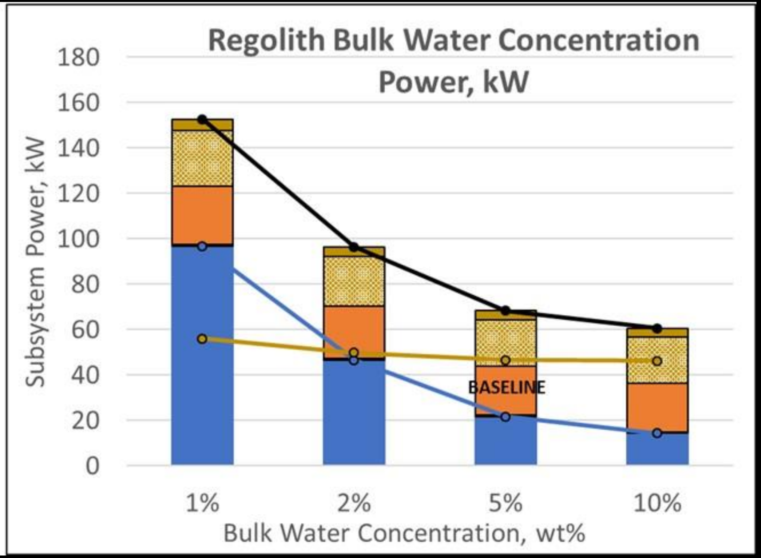
Polar Water Mining System Mass and Power Estimates*



- Mass and power scale 'linearly' due to modularity of major elements

Pilot Scale **Initial Full Scale**





- Bulk water concentration is water content over the mine depth. Includes any heterogeneities
  - Values chosen are consistent with possible interpretations of Neutron data
- The water extraction system drives results.
  - Water extractor subsystem reaches scalability limit, so multiple units are needed; increasing mass and power particularly at 1 wt%
  - At higher concentrations there is less impact since minimum number of units is reached
- 1wt% is unlikely to be a viable ISRU water-ice deposit (for these assumptions)

*"Case Study for Lunar ISRU Systems Utilizing Polar Water", AIAA ASCEND, 16-18 Nov., 2020

Comparison of Water Ice to O_2 from Regolith Mining at Initial Scale

Mission Study Assumption Differences

Mass

- The ISRU system, without the lander and bus was used for the comparison
- The O_2 system included solar panels for power, this mass was subtracted since the water system does not include power
- The O_2 system requires hydrogen from earth whereas the water system produces this. An approximation of the hydrogen mass and tank was added.

Power

- The water system power disregards thermal versus electrical power; assumes even thermal (heating) must come from electrical source
- The O_2 system uses a solar concentrator to supply direct heating to the regolith for reaction.

Water Ice ISRU System		O_2 from Regolith ISRU System	
Total Mass	**4.9 mT**	**2.7 mT**	
Ridge System	2.6 mT	*ISRU system*	0.429 mT
Mine system	0.49 mT	*H_2 from earth*	2.3 mT
2 water Tankers	1.8 mT		
Total power	**68 kW**	**45 kW**	
Ridge Power	*46 kW*	*Electrical*	*11.8 kW_e*
Mine Power	*22 kW*	*Direct thermal*	*33.3 kW_t*

"Lunar Production System for Extracting Oxygen from Regolith", ASCE Earth & Space, 4/2021
J. Aerosp. Eng., 2021, 34(4): 04021043

"Case Study for Lunar ISRU Systems Utilizing Polar Water", AIAA ASCEND, 16-18 Nov., 2020

Comparison of Water Ice to O_2 from Regolith Mining at Initial Scale

Results

Water Ice	O_2 from Regolith
4.9 mT	2.7 mT *each successive mission will require 2 mT of hydrogen from earth, so mass favorably is lost at 2nd mission.
68 kW	45 kW
Resource is not yet characterized, exploration is required prior to operations to determine extent.	Resource is largely known from returned Apollo samples and orbital instruments.
Highly reliant on location with accessibility challenges; likely requires higher traverse distances and some operations in an extreme environment (PSR).	The resource is very accessible and ubiquitous.
This case study requires operations at two locations.	Case study does full operations at one location.
Thermal energy for resource extraction is lower; water vaporization energy.	Thermal energy for resource extraction is high, requires melting of regolith
Use of non-electrical heat sources is challenging.	The system can use direct solar thermal heating to reduce electrical power.
Provides full propellant for vehicles. Water can also be used for other applications.	Only oxygen is provided.

"Case Study for Lunar ISRU Systems Utilizing Polar Water", AIAA ASCEND, 16-18 Nov., 2020

ISRU Commodity Production Summary and Next Step Priorities

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

- **Expand Development of Metal/Aluminum Extraction & other Feedstock for Manufacturing & Construction**
  - Continue and expand work on combined oxygen and metal extraction technologies;
  - Initiate work focused on metal extraction and processes leading to more pure/refined metals
  - Consider wider range of regolith options: Mare regolith, Pyroclastic Glasses, and KREEP
  - Continue and expand construction feedstock/commodity development with in-space manufacturing and construction
  - Evaluate synthetic biology technologies for bio-mining, bio-plastic, and some commodity feedstocks

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

- **Initiate Internal and Industry-led System-level integration of ISRU and infrastructure capabilities**
  - Expand ISRU system engineering, modeling, integration, and testing to enable technology and system selections
  - Begin combining power, excavation, ISRU, storage & transfer, comm/nav, autonomy/avionics, maintenance/crew.

- **Initiate solicitations with Industry to progress ISRU technologies to Demonstration & Pilot-scale flights**
  - Pursue oxygen and metal extraction demonstrations; delay water mining demonstration until better knowledge is obtained
  - Provide feedstock technologies and capabilities to support construction demonstrations

Thank you.

Questions?

www.nasa.gov/spacetech

Backup

What are the Challenges? - ISRU Development & Implementation

Space Resource Challenges

R1 What resources exist at the site of exploration that can be used?

R2 What are the uncertainties associated with these resources?
Form, amount, distribution, contaminants, terrain

R3 How to address planetary protection requirements?
Forward contamination/sterilization, operating in a special region, creating a special region

ISRU Technical Challenges

T1 Is it technically and economically feasible to collect, extract, and process the resource?
Energy, Life, Performance

T2 How to achieve high reliability and minimal maintenance requirements?
Thermal cycles, mechanisms/pumps, sensors/ calibration, wear

ISRU Operation Challenges

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

O2 How to operate in low gravity or micro-gravity environments?
Drill/excavation force vs mass, soil/liquid motion, thermal convection/radiation

O3 How to achieve long duration, autonomous operation and failure recovery?
No crew, non-continuous monitoring, time delay

O4 How to survive and operate after long duration dormancy or repeated start/stop cycles with lunar sun/shadow cycles?
'Stall' water, lubricants, thermal cycles

ISRU Integration Challenges

I1 How are other systems designed to incorporate ISRU products?

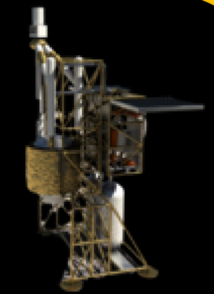
I2 How to optimize at the architectural level rather than the system level?

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

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

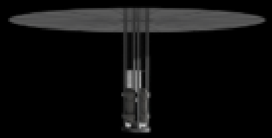
Addressing Sustainable Operations
NASA Lunar Surface Innovation Initiative (LSII)

In Situ Resource Utilization
Collection, processing, storing and use of material found or manufactured on other astronomical objects



Surface Excavation/Construction
Enable affordable, autonomous manufacturing or construction

Sustainable Power
Enable continuous power throughout lunar day and night



Lunar Dust Mitigation
Mitigate lunar dust hazards

Extreme Access
Access, navigate, and explore surface/subsurface areas

Extreme Environments
Enable systems to operate through out the full range of lunar surface conditions

- LSII is developing the technologies required for establishing lunar infrastructure across these six primary areas.
- LSII will accelerate technology readiness for key components and systems and provide early technology demonstrations which will help to inform relative SMD activities and development of HEO crewed flight systems.

LSII works across industry, academia and government through in-house efforts and public-private partnerships to develop transformative capabilities for lunar surface exploration.

ISRU Functional Breakdown And Flow Diagram

Destination Reconnaissance and Resource Assessment

- Site Imaging/Terrain Mapping
- Instruments for Resource Assessment
- Orbital Resource Evaluation
- Local Surface Resource Evaluation
- Resource/Terrain/Environment Data Fusion and Analyses

Resource Acquisition, Isolation, and Preparation

- Resource Excavation & Acquisition
- Resource Preparation before Processing
- Resource Transfer
- Resource Delivery from Mine Site and Removal

Resource Processing for Production of Mission Consumables

- Resource Storage and Feed To/From Processing Reactor
- Regolith Processing to Extract Oxygen
- Regolith Processing to Extract Water
- Carbon Dioxide Processing
- Water Processing
- Instrumentation to Characterize Processing Performance
- Product/Reactant Separation
- Contaminant Removal from Reagents/Products

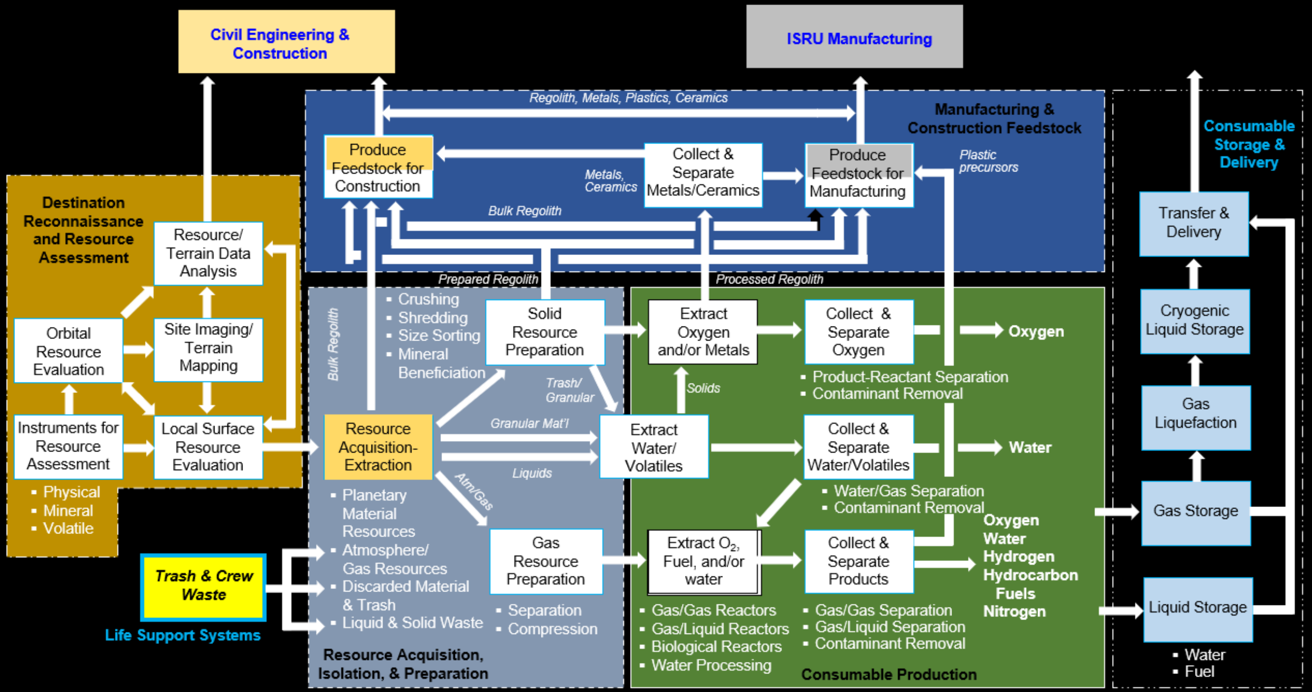
Resource Processing for Production of Manufacturing and Construction Feedstock

- In Situ Excavation and Movement for Construction
- Resource Preparation for Construction Feedstock
- Material transfer
- Resource Processing to Extract Metals/Silicon
- Resource-Trash/Waste Gas Processing to Produce Methane/Plastics

Cross Cutting

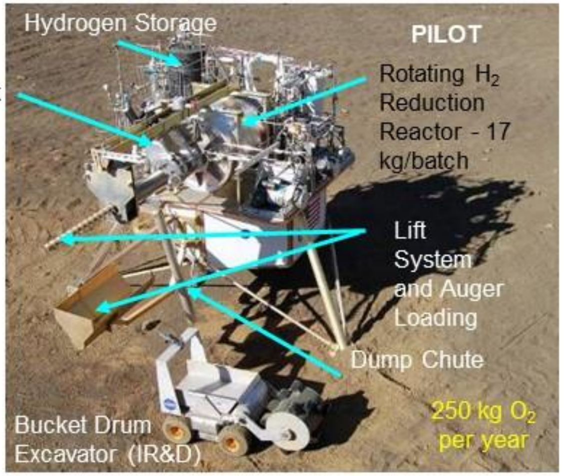
- Planetary Simulants for Test & Verification
- Planetary Regolith/Environment Test Chambers

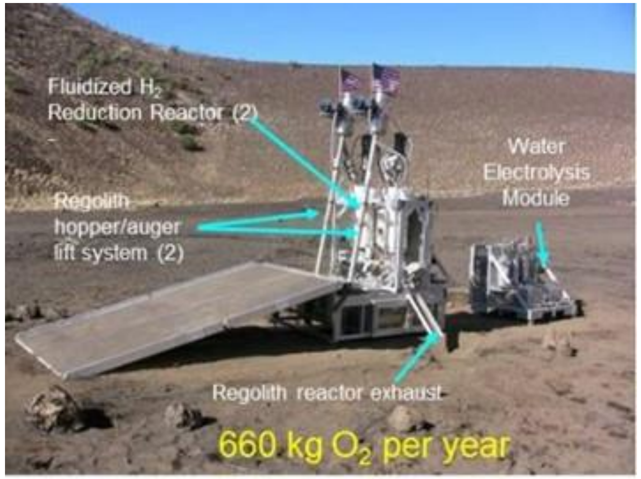
- Functional Breakdown and Flow Diagram used to understand:
  - Technology State of the Art and gaps
  - Connectivity Internally and with other disciplines
  - Influence of technologies on complete system and other functions
- ISRU functions have shared interest with Autonomous Excavation, Construction, & Outfitting (AECO)
  - Destination Reconnaissance
  - Resource Excavation & Delivery
  - Construction Feedstock Production



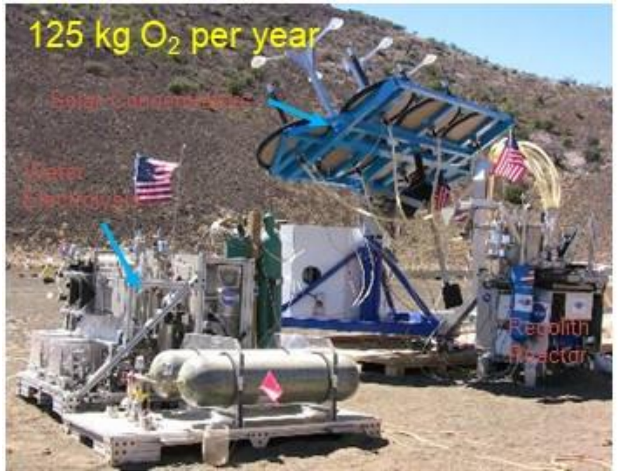
Oxygen from Regolith – Overview/Past Development (Constellation)

- **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
  - Lunar polar regolith primarily Highland-type: >75% anorthite, iron poor
- **Over 20 processes have been identified to extract the oxygen**
  - Several have been evaluated in the lab to TRL 3 at subscale
  - As processing temps increase, O_2 yield increases, and technical and engineering challenges increase
  - ➢ **Work during the Constellation Program focused on three processes**
    - Hydrogen reduction: ‘low’ temperature, low yield (1 to 5 wt%), high TRL
    - Carbothermal reduction: ‘higher’ temperature, medium yield (5 to 15 wt%), medium TRL
    - Molten regolith electrolysis: ‘high’ temperature, high yield (>20 wt%), low TRL
    - ❖ Note: Other technologies were also evaluated under internal and SBIR contracts
- **Two processes developed to TRL 4-5 at human mission relevant scale**





Hydrogen (H_2) Reduction - 2008

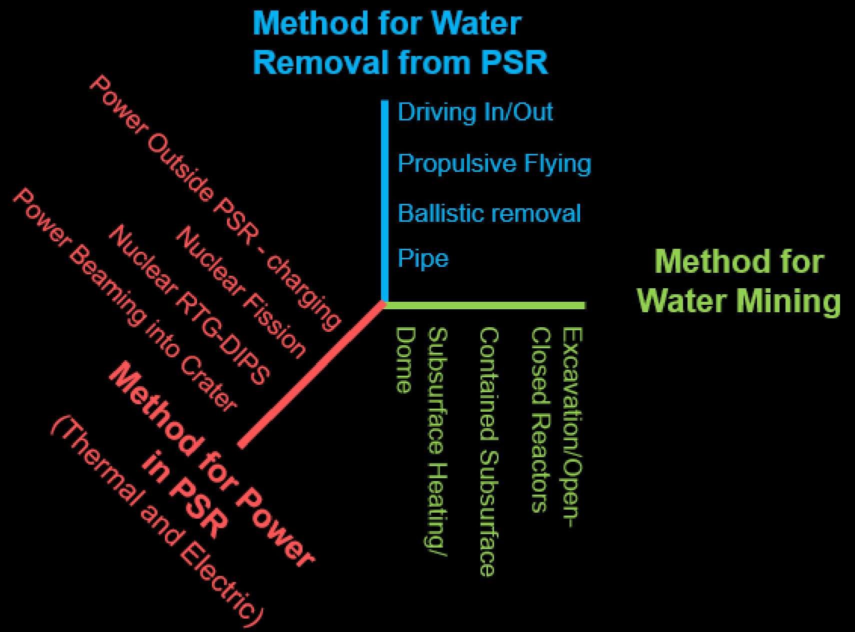


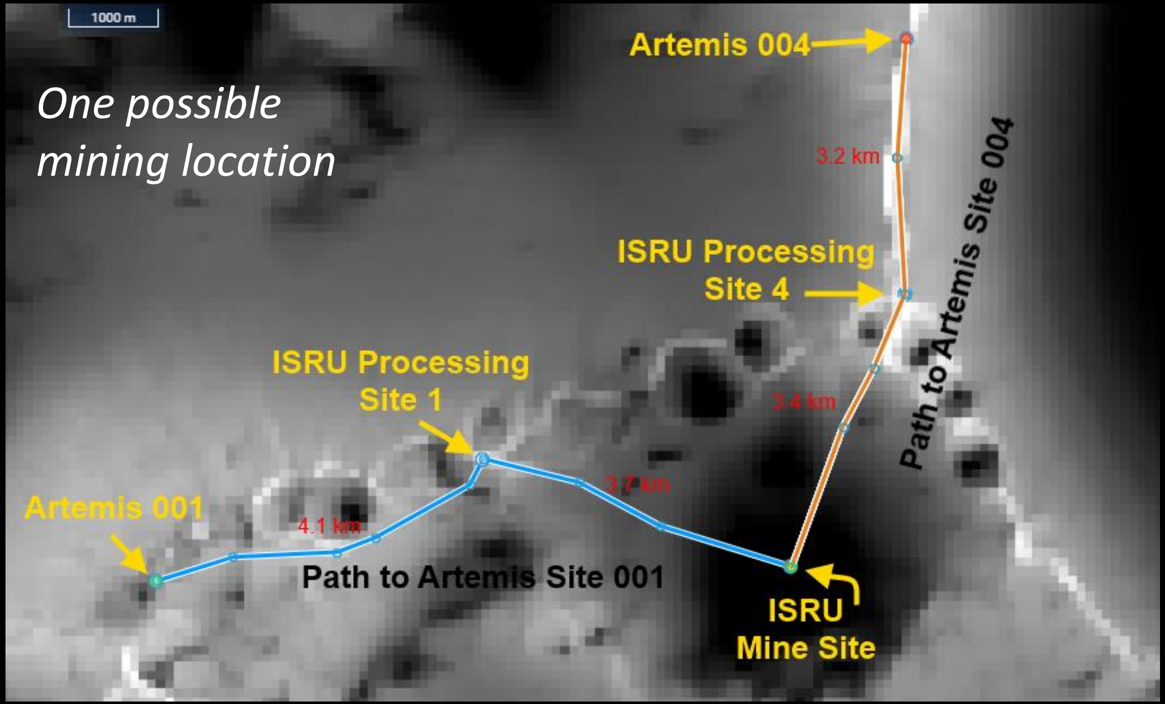
Carbothermal (CH_4) Reduction - 2010

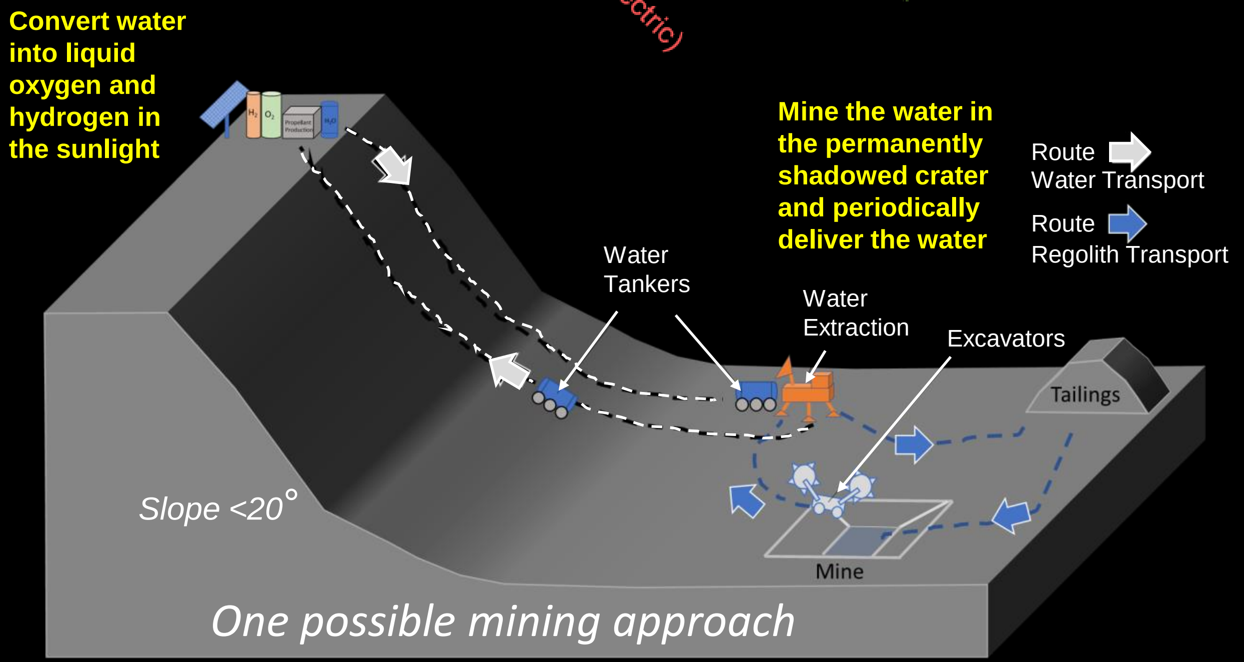
Polar Ice/Water Mining - Overview

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

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







Polar Ice/Water Mining – Current Development

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

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

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

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

Oxygen (Metal) from Regolith - Current Development

Oxygen Extraction Methods under development:

1. Carbothermal Reduction
    - Carbothermal Reduction Reactor Design – Sierra Nevada Corp (SNC) – 2 SBIR Phase IIIs, and COPR Tipping Point
    - CaRD - Carbothermal Reduction Demonstration – GCD JSC
2. Molten Regolith Electrolysis (MRE)
    - Molten Regolith Electrolysis - Lunar Resources – NASA SBIR Phase I/II and NSF SBIR Phase II
    - Molten Regolith Electrolysis Tech Maturation – KSC – GCD and ECI
3. Ionic Liquid Reduction and Electrolysis reactors for O2/metals
    - RRILE – Resource Recovery with Ionic Liquid for Exploration - MSFC – GCD - Completed
    - Ionic Liquid-Assisted Electrochemical Extraction of Oxygen - Faraday Technology - SBIR Phase I – Completed
4. Plasma Hydrogen Reduction
    - Plasma Hydrogen Process – KSC – CIF
5. Moon to Mars Oxygen and Steel Technology (CO/H_2 Reduction) - Pioneer Astronautics - SBIR Phase II Sequential
6. Carbothermal/Vapor Pyrolysis with Solar Concentrator – Blueshift - SBIR Phase I – Completed

Not funded by NASA

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

Water Processing – Current Related* Development

*Not all funded efforts are designated as ISRU

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

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

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

*Not all funded efforts are designated as ISRU

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

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

*Not all funded efforts are designated as ISRU

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