EXPLORESPACE TECH
TECHNOLOGY DRIVES EXPLORATION

In Situ Resource Utilization (ISRU) - Surface Excavation & Construction

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Gerald Sanders | ISRU System Capability Lead | NASA Space Technology Mission Directorate

In Situ Resource Utilization – Surface Excavation and Construction

Driving Outcomes

LEAD	THRUSTS	OUTCOMES
Ensuring American global leadership in Space Technology • Lunar Exploration building to Mars and new discoveries at extreme locations • Robust national space technology engine to meet national needs • U.S. economic growth for space industry • Expanded commercial enterprise in space	***Go*** *Rapid, Safe, & Efficient Space Transportation*	• Enable Human Earth-to-Mars Round Trip mission durations less than 750 days. • Enable rapid, low cost delivery of robotic payloads to Moon, Mars and beyond. • Enable reusable, safe launch and in-space propulsion systems that reduce launch and operational costs/complexity and leverage potential destination based ISRU for propellants.
	Land *Expanded Access to Diverse Surface Destinations*	• Enable Lunar and Mars Global Access with ~20t payloads to support human missions. • Land Payloads within 50 meters accuracy while also avoiding local landing hazards.
	Live *Sustainable Living and Working Farther from Earth*	• Conduct Human/Robotic Lunar Surface Missions in excess of 28 days without resupply. • Conduct Human Mars Missions in excess of 800 days including transit without resupply. • Provide greater than 75% of propellant and water/air consumables from local resources for Lunar and Mars missions. • Enable Surface habitats that utilize local construction resources. • Enable Intelligent robotic systems augmenting operations during crewed and un-crewed mission segments.
	Explore *Transformative Missions and Discoveries*	• Enable new discoveries at the Moon, Mars and other extreme locations. • Enable new architectures that are more rapid, affordable, or capable than previously achievable. • Enable new approaches for in-space servicing, assembly and manufacturing. • Enable next generation space data processing with higher performance computing, communications and navigation in harsh deep space environments.

In Situ Resource Utilization (ISRU)

- **Resource Mapping/Estimation:** Enable global and detailed local and subsurface mapping of lunar resources and terrain, especially for water in permanently shadowed craters, for science, future exploration, and commercial use
- **Oxygen Extraction:** Enable extraction and production of oxygen from lunar regolith to provide 10's of metric tons per year, for up to 5 years with little human involvement and maintenance, for reusable surface and ascent/descent transportation.
- **Water Mining:** Enable cis-lunar commercial markets through extraction of water resources to provide 100's of metric tons of propellant per year for reusable landers and cis-lunar transportation systems

Advanced Materials, Structures and Manufacturing (AMSM)

- **Lunar Surface Construction** for building of roads, launch/landing pads, dust free zones, foundations, blast protection, radiation shielding, shade structures, unpressurized shelters, and even pressurized habitats.

Space Resources

- **'Resources'**
  - Traditional**:** **Water**, atmospheric gases, volatiles, solar wind volatiles, oxygen & metals, etc.
  - Non-traditional: Trash and wastes from crew, spent landers and residuals, etc.
- **Energy**
  - Thermal Energy Storage Using Modified Regolith
  - Permanent/Near-Permanent Sunlight (Stable thermal and power generation)
  - Permanent/Near-Permanent Darkness (Thermal heat sink)
  - Large Thermal Gradients
- **Environment**
  - Vacuum
  - Micro/Reduced Gravity
- **Location**
  - Stable Locations/'Real Estate': Earth viewing, sun viewing, space viewing, staging locations
  - Isolation from Earth: Electromagnetic noise, hazardous activities, extraterrestrial sample curation & analysis, storage of vital information, etc.

Lunar Resources

Polar Water/Volatiles

- Form, concentration, and distribution of Water in shadowed regions/craters is not known
  - **LCROSS estimates 5.5 wt%**
  - Other volatiles (H_2, CO, CO_2, CH_4, NH_3)
- Provides 100% of chemical propellant mass
- Polar water is "Game Changing" and enables long-term sustainability

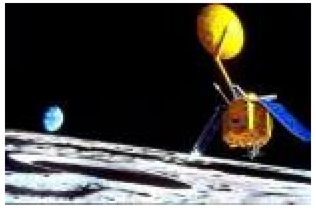
Lunar Regolith

- **>40% Oxygen by mass**
  - Silicate minerals make up over 90% of the Moon
- Regolith
  - Mare: Basalt (plagioclase, pyroxene, olivine)
  - **Highland/Polar**: >75% anorthite, iron poor
  - Other constituents: KREEP, Pyroclastic Glass, Solar Wind Volatiles (H, C, N, He)
- Provides >75% of chemical propellant mass

Lunar In Situ Resource Utilization

'Prospect to Product'

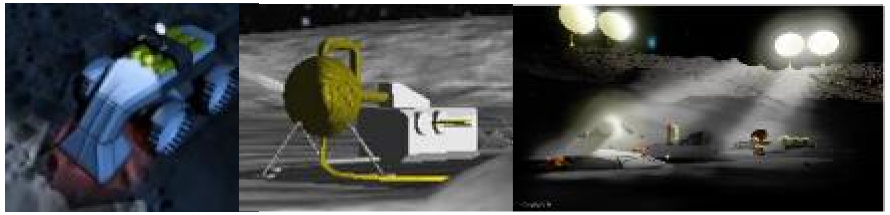
Resource Assessment – Looking for Water/Minerals



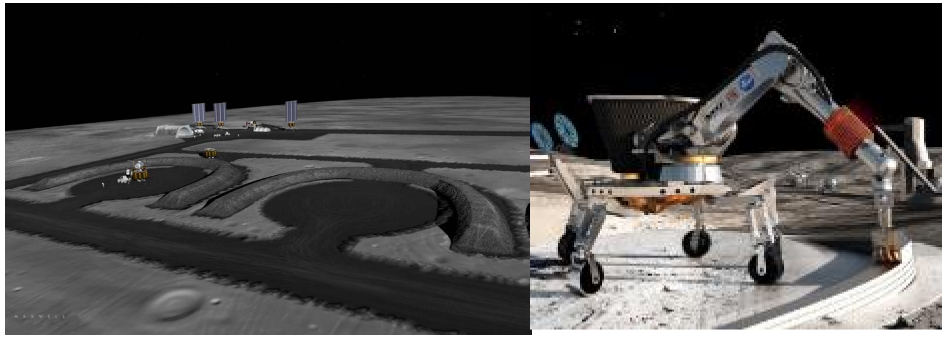
Global Assessment

Local Assessment

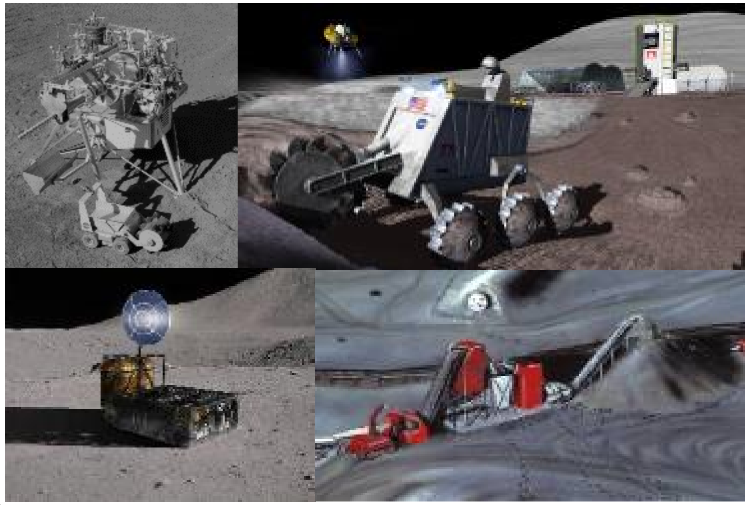
Mining Polar Water & Volatiles



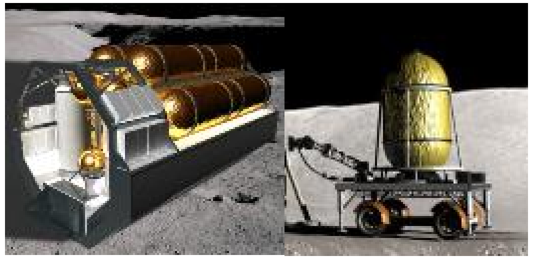
Landing Pads, Berms, Roads, Shielding and Structure Construction



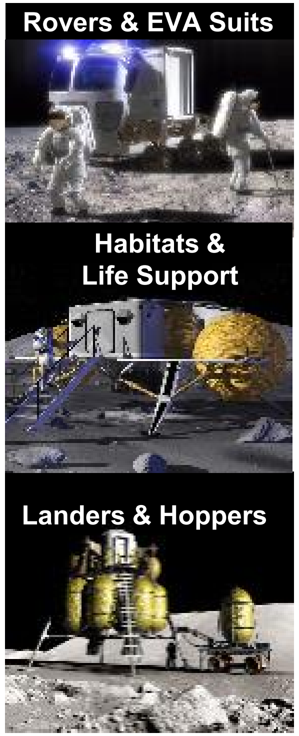
Excavation & Regolith Processing for O_2 & Metal Production



Consumable Storage & Delivery



Consumable Users

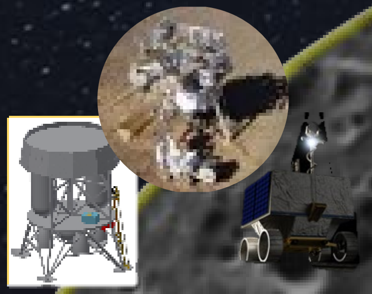


Implementing ISRU Requires Multiple Disciplines and Technical Areas to Work Together

Lunar ISRU Strategy: Leader/Follower

SpaceTech has a leader/follower path defined for lunar ISRU which relies on lunar demonstrations on CLPS missions

- Ice mining (Leader) – Potential to provide LO_2/LH_2 propulsion, crew consumables, and water for radiation protection
- O_2 Extraction (Follower) – Provide oxidizer and crew consumables



Precursors and demonstrations

- Leader: Volatile prospecting with PRIME-1 & VIPER (2022)
- Follower: O_2 from Regolith high-fidelity ground demo in TVC with flight demo in mid 2020s

Knowledge gained from precursors and demonstrations will inform the decision for Pilot and Full-scale Plants

Pilot Plant

- Relevant scale plant (100's of kg/yr)
- Demonstrates core capabilities and subsystems
- Products available for SMD, HEOMD, or commercial partners
- Can be scaled up to Full scale mission production rates

Why Use Space Resources?

- **Using Space Resources can reduce mission and architecture mass and costs**
  - **Launch mass savings** (gear ratio)
  - **Reduce launch numbers**
  - **Reduce costs** (less launchers/reuse assets)
  - **Supports terrestrial industry/Enables space commercialization**

- **Using Space Resources can increase safety for crew and mission success**
  - **Ensure and enhance crew safety** (repair, consumables, shielding)
  - **Provide critical solutions for mission assurance**
  - **Minimizes impact of shortfalls in other system performance** (launchers, landers/ascent, life support)
  - **Enhance crew psychological health**

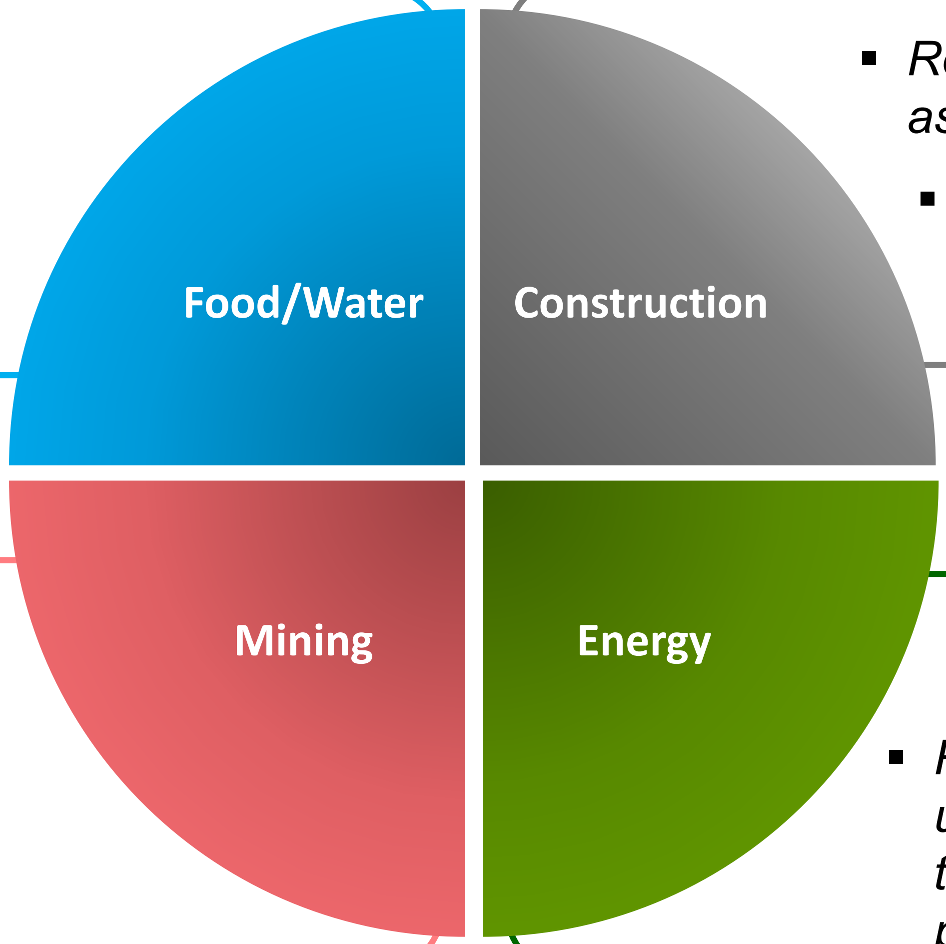
- **Using Space Resources can enhance or enable new mission capabilities**
  - **Mission life extensions and enhancements**
  - **Increased surface mobility and access**
  - **Increased science**

- **Learning to use Space Resources can help us on Earth**

Space Resource Utilization Is Synergistic with Terrestrial Needs

- *Improve water cleanup techniques*
- *Advance food/plant growth techniques and nutrient production*

- *Reduce or eliminate cement and asphalt – renewable materials*
  - *Alternative construction techniques – 3-D printing*

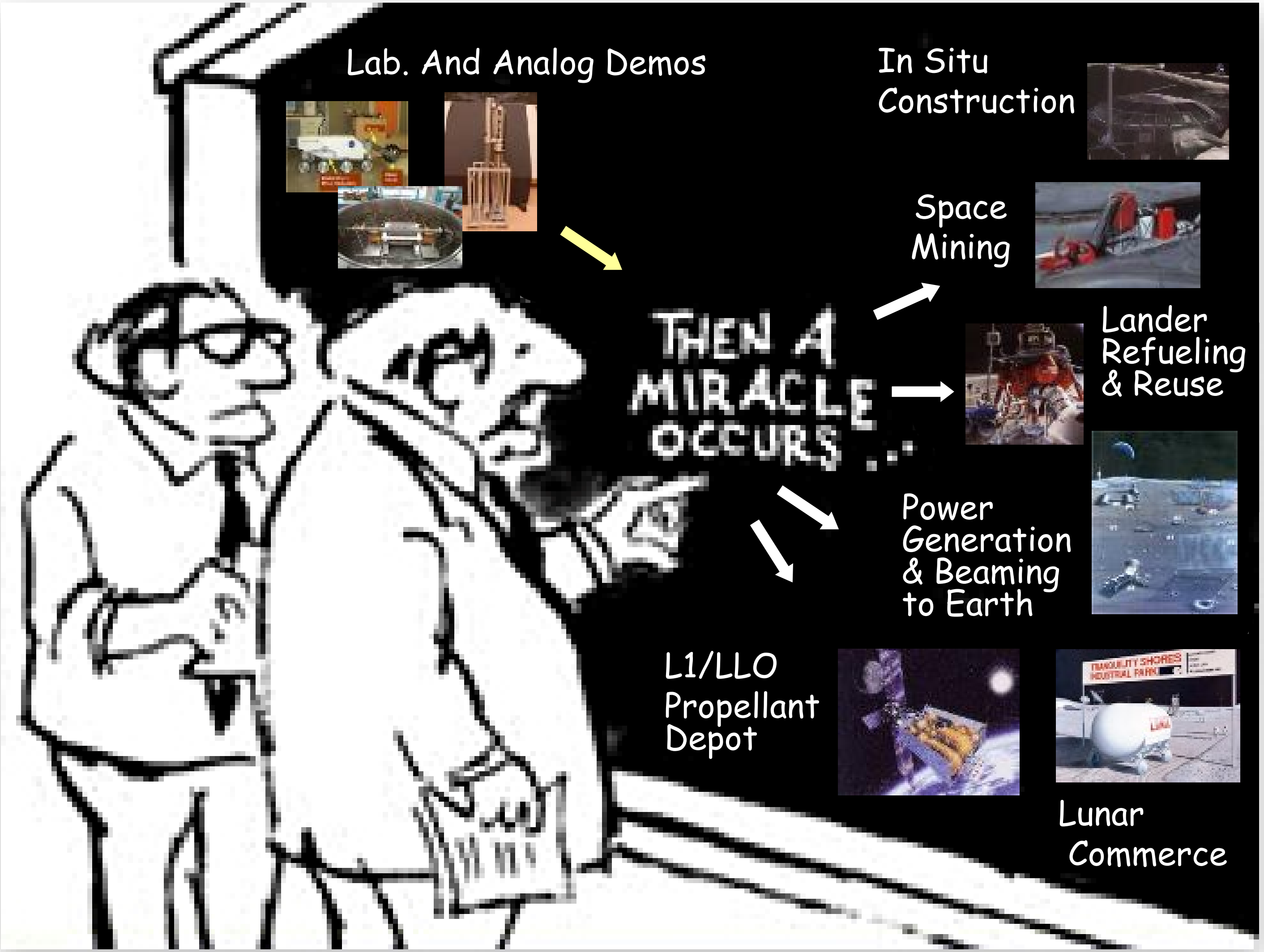


- *Increase safety*
- *Reduce maintenance*
- *Increase mining and processing efficiency*
- *Reduce CO_2 emissions*

- *More efficient power generation, storage and distribution*
- *Reduce or eliminate petroleum/gas usage (CO_2 Reduction) – Use sun, thermal, trash, and alternative fuel production*

Promote *Reduce, Reuse, Recycle, Repair, Reclamation*
…for benefit of Earth, and living in Space.

Early ISRU Development & Implementation Plan



"I think more work is needed in this step."

Strategy For ISRU Insertion into Human Exploration

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

- **Know Customer Needs and Gaps**
  - Work with Artemis elements and Moon/Mars Surface Architecture
  - Work with Industry/Academia: Lunar Surface Innovation Consortium
- **Perform Ground Develop of Hardware and Systems until Flight**
  - Develop and advance ISRU technologies to enable acquisition of resources and processing into mission consumables
  - Develop lunar ISRU components and subsystems with a Mars-forward application
  - ➢ **Engage industry and Academia** to lay the foundation for long-term lunar economic development
- **Utilize CLPS Precursor Missions**
  - Understand lunar polar resources for technology development, site selection, mission planning
  - Obtain critical data (ex. regolith properties, validate feasibility of ISRU process)
  - Demonstrate proof-of-concept and reduce risk
  - Demonstrate critical ISRU hardware and validate Pilot/Full scale designs
- **Perform End-to-End ISRU Production Pilot Mission** at sufficient scale to eliminate risk of Full scale system
  - Utilize product from Pilot mission in subsequent human lander mission (ex. oxygen for EVA or extended stay)
- **Design and Fly 'Full' Scale ISRU Production Capability** around redundant modules with margin for reusable lander and/or hopper

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

Influence, Needs, and Products with Other Mission Elements

To obtain full benefits of ISRU, the architecture and mission elements ('Customers') need to be designed from the start to be able to utilize ISRU

Mission Elements	ISRU-Construction Influence	ISRU-Construction Needs	ISRU-Construction Products
Descent/Ascent Vehicles	- Propellant options - Descent/ascent vehicle size & available payload capability - Lander/ascent vehicle Delta-V/ Rendeqvous Orbit - Lander/engine configuration - Lander servicing design and capability - Reusability/Surface Hopping	- Vehicles designed to use ISRU produced propellants - Propellant specifications - Propellant quantities per mission or year	- O_2, H_2, CH_4, other hydrocarbons - Landing pads, berms, protection, depots, and servicing
In-Space/Transit Vehicles	- Propellant options - Delta-V/Rendezvous Orbit - Low-thrust/orbital drag makeup	- Vehicles designed to use ISRU produced propellants - Propellant specifications - Propellant quantities per mission or year	- O_2, H_2, CH_4, other hydrocarbons - Waste Gases from Trash - Ar
Power Systems	- Total power generation requirement - Power generation technology selections - Power thermal and electrical storage options with local resources - Potential for common technologies	- Significant amounts of electrical and thermal power - Power in Permanently Shadowed Regions (PSRs)	- Fuel cell reactants: O_2, H_2, CH_4 - Thermal storage with in situ materials
Habitats - Life Support Systems	- Degree of air/water loop closure and Earth-delivered logistics - Potential for common technologies - Radiation shielding capabilities - Construction for hardware protection - Construction for expanded crew usage; food, science, living, etc.	- Alternative uses for waste gases and trash - Consumable specifications - Consumable quantities per year - Radiation allowance/specifications - Habitable volumen specifications/needs	- O_2, water, (N_2 on Mars) - Regolith/construciton for shielding - Plastics for manufacturing & shielding - Metals for manufacturing

ISRU Incremental Growth
Phases of Evolution and Use

Demonstrate, Build Confidence, Increase Production and Usage

10 to 30 mT Range for Initial Full Scale Production

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

NPS = Near Permanent Sunlight

PSR = Permanently Shadowed Region

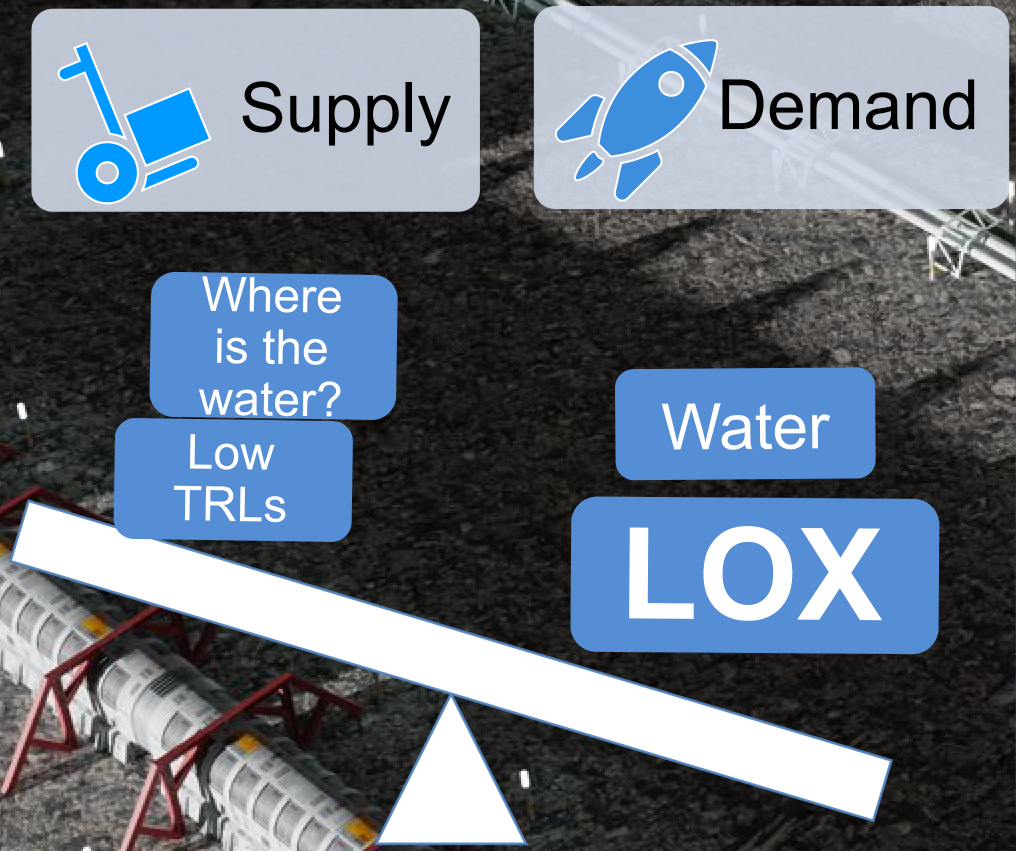
[1]Estimates from rocket equation and mission assumptions

[6]Information obtained from presentation at LSIC Supply & Demand Workshop. Presentations/videos posted at the LSIC website http://lsic.jhuapl.edu/Events/103.php

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

LSII | ISRU Industry Propellant Supply and Demand Workshop

A dozen industry talks with discussions during a half day virtual workshop in September, 2020.
Over 200 attendees from over 100 institutions (recording at http://lsic.jhuapl.edu/Events/103.php?id=103)



Strong demand projected for in-situ derived propellant.

- Industry based on actual plans and hardware
- 10s to 100s of metric tons of propellants a year, near term (within a decade)
- 80% of the demand is LOX
- NASA and DOD can serve as anchor customers to ensure initial viability for this new marketplace

Two potential supply options

- Water (O_2 and H_2) from ice. (technology TBD)
- O_2 directly from regolith. (two possible technologies)

Supply challenges

- Low TRL of extraction equipment for ice and O2R.
- Insufficient knowledge of water as a reserve.

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?

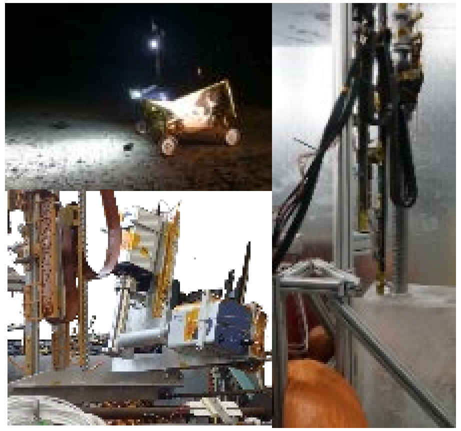
I3 How to manage the physical interfaces and interactions between ISRU and other systems?

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

What Is Still Needed? ISRU Capability Gaps (1 of 2)

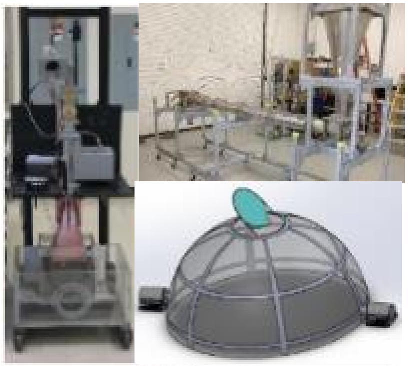
Resource Assessment Capability Gaps

- Surface features and geotechnical data on regolith outside and inside permanently shadowed craters (PSRs)
- Understanding of water and contaminants as a function of depth and areal distribution
- Understanding of subsurface water/volatile release with heating
- Resolution of hydrogen and subsurface ice at <10's m scale (or less) for economic assessment & mine planning (orbital/surface)
- Instrument for polar regolith sample heating and released volatile characterization (minimum loss during transfer/evaluation)
- Long duration operations at <100 K temperatures and lunar vacuum
- Traversibility inside and in/out of PSRs
- Increased autonomy and better communications into PSRs
- Long-duration mobile polar resource assessment operations (nuclear or power beaming)



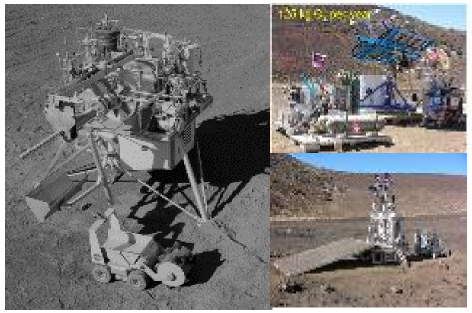
Mining Polar Water Capability Gaps

- Limited knowledge/understanding of polar water depth, distribution, concentration to at least 1 m below the surface and multiple sq km.
- Limited knowledge/understanding of regolith properties within PSR
- Feasibility and operation of downhole ice/water vaporization and collection in cold-trap under lunar PSR conditions
- Feasibility and operation icy regolith transfer and processing in reactor under lunar PSR conditions
- Other volatile capture and separation; contaminant removal
- Water electrolysis, clean-up, and quality measurement for subsequent electrolysis or drinking (10,000's kg)
- Long-term operation under lunar PSR environmental conditions (100's of days, 10,000's kg of water)
- Electrical power & Thermal energy in PSRs for ice mining/processing (10's of KWs)



Oxygen Extraction Capability Gaps

- Increase scale of regolith processing by 1 to 3 orders to reach minimum of 10 mT O_2/yr (depending on method)
- Increase duration operation under lunar environmental conditions (100's of days, 10,000's kg of O_2)
- Long-life, regolith transfer (100's mT) and low leakage regolith inlet/outlet valves (10,000's cycles)
- Deployable large scale solar collection/thermal energy transfer for regolith melting
- Regenerative oxygen clean-up for direct oxygen production (10,000's kg)
- Water electrolysis, clean-up, and quality measurement for subsequent electrolysis or drinking (10,000's kg)
- Autonomous process monitoring, including measuring mineral properties/oxygen content before and after processing



Surface Excavation and Construction Capability Gaps (2 of 2)

Excavation & Delivery Capability Gap
- Excavation and sample transfer for science and ISRU demonstrations
- Excavation of hard regolith/ice material
- Long-duration operation of mechanisms
- Long-distance (100's km) travel and traversibility over same mining location
- Increased autonomy of operations

Surface Construction Capability Gaps
- Material and construction requirements and standards
- Long-duration operation of mechanisms; scale of construction activities
- Hardware operation and product quality under lunar environmental conditions
- Increased autonomy of operations

CRATOS - 2008

Centaur Excavator - 2010

RASSOR

Competitions

Grading & Leveling Blade

Compactor Roller

Paver Deployment

Additive Construction

Molds - Grown

ISRU & Surface Construction Technology Development* (1 of 5)

Lunar Polar Ice Resource Assessment

Impacts due to FY21 Appropriations in work

- **Acquire Icy Regolith Samples**
  - Fundamental Regolith Properties Project - Bulk water stability – NASA GRC
  - Characterization of Lunar Polar Volatiles for Curation and ISRU – NASA JSC
  - ColdARM – JPL
  - Trident Auger – Honeybee Robotics
- **Instruments for Physical/Geotechnical Characterization**
  - Material Characterization while Drilling on Lunar/Martian Surface – ESI with CSM
  - SPARTA – Honeybee Robotics; Cone penetrometer/shear vane (part of ColdArm)
  - Microscope/Camera – JPL; (part of ColdArm)
  - High TRL Rover Lidar – NASA GSFC
  - Moon-Mars Ice Challenge – NASA LaRC
- **Instruments for Mineral Characterization**
  - Fundamental Regolith Properties Project - Bulk water stability – NASA GRC
  - LIBS – BigIdeas Challenge by Univ. of Penn.
  - *Recent SMD CLPS Selections*
- **Instruments for Ice/Volatile Characterization**
  - Polar Resources Ice Mining Experiment-1 – NASA KSC & Honeybee Robotics
  - Light Water Analysis & Volatile Extraction (Light WAVE) – NASA JSC
  - Planetary Volatile Extractor (PVEx) – Honeybee Robotics
- **Mobility and Instruments for Resource Assessment**
  - L-Puffer/CADRE – JPL; Mini-rover w/ TBD instruments
  - MoonRanger – SMD DALI; Mini-rover w/ camera (2022)
  - NeuRover – SBIR Phase II; Mini-rover w/ neutron spectrometer
  - Robotic Technologies Enabling the Exploration of Lunar Pits – Phase III Carnegie Mellon
  - Mobile Autonomous Prospecting Platform) – Lunar Outpost

Selected for CLPS

**Blue Italic = SMD Funded*
^HEOMD/STMD/SMD Funded

Mineral

★ ★ NIRVSS – InfraRed Spec ^
★ *L-CIRiS – Compact InfraRed Imaging System*
eXTraterrestrial Regolith Analyzer for Lunar Soil – XRD/XRF
Ultra-Compact Imaging Spectrometer – shortwave IR
BECA – gamma ray spectrometer w/ pulsed neutrons

Volatile Direct Measurement

★★★★ MSOLO – mass spectrometer ^
★ *PITMS – ion trap mass spectrometer*
CRATER – laser based mass spectrometer

Hydrogen Measurement

★ ★★ NSS – Neutron Spectrometer ^
★ *Neutron Measurements at the Lunar Surface*

Imager

★ *Heimdall – digital video recorder/4 cameras*
ColdARM – microscope/camera

Regolith Acquisition

PlanetVac – pneumatic transfer ^
SAMPLR – arm scoop
ColdARM – arm scoop
★★ Trident – auger drill
PVEx – Coring drill

Extreme Access – MicroRovers/Hoppers

CubeRover (SBIR)
★ *MoonRanger (LSITP)*
L-PUFFER/CADRE (JPL)
NeuRover (SBIR)
Big Ideas Challenge (Universities)
Small Deployable Hopper (TP)

★ Astrobotics 2021
★ Masten 2022
★ PRIME-1 2022
★ VIPER 2023

ISRU & Surface Construction Technology Development* (2 of 5)

Lunar Polar Mining

*Impacts due to FY21 Appropriations in work

- **Demonstrate feasibility and operation icy regolith transfer and processing in reactor under lunar PSR conditions**
  - Fundamental Regolith Properties Project - Bulk water stability – NASA GRC
  - Characterization of Lunar Polar Volatiles for Curation and ISRU – NASA JSC
  - Material Characterization while Drilling on Lunar/Martian Surface – ESI with Colorado School of Mines (CSM)
  - Lunar Auger Dryer (LADI) with inlet/outlet – NASA JSC
  - Regolith Valve project – NASA GRC
  - Motors for Dusty Environments/Bulk Metallic Glass Gears
  - Aqua Factorem-Ice Crystal Sifting – UCF NIAC Phase I
- **Demonstrate feasibility and operation of downhole ice/water vaporization and collection in cold-trap in the lunar PSR**
  - PVEx: Coring drill with cryo capture – Honeybee Robotics *(SBIRs)*
  - Thermal Management System for Lunar Ice Miners – SBIR Phase I w/ Advanced Cooling Tech tied to PVEx/Honeybee
  - LPMO: subsurface heating & volatile removal via microwave/RF/IR energy – TransAstra NIAC Phase II
  - Thermal Mining: subsurface heating & volatile removal via solar energy – CSM NIAC Phase I (Completed)
- **Water capture, clean-up, quality measurement and electrolysis (10,000's kg/yr)**
  - Lunar water simulant definition – CIF and Simulant Project
  - IHOP PEM Water Electrolysis/Clean-up – Paragon BAA
  - Solid Oxide Electrolysis: 3 contracts with OxEon (SBIR Phase II, BAA, and TP)
  - Dirty Water Alkaline Electrolysis – Teledyne BAA
  - Regenerative Fuel Cell Project – GRC
  - Lunar Propellant Production Plant (LP3) – Skyre TP
  - Integrating Thermal Processing of Lunar Ice and Solid Oxide Electrolysis for LH_2/LO_2 Production – CSM/OxEon TP
  - Advance Alkaline Reversible Cell/Dirty Water – pH Matter TP and ACO

ISRU & Surface Construction Technology Development* (3 of 5)
Oxygen Extraction

*Impacts due to FY21 Appropriations in work

- **Increase scale of regolith processing by 1 to 3 orders; Increase duration operations in lunar environmental**
  - Carbothermal Reduction reactor, feed/removal system, and reactant control – SNC, JSC, GRC with TP & 2 SBIR Phase III
  - Molten Regolith Electrolysis – KSC GCD & ECI; 2 SBIR Phase I – Lunar Resources
  - Ionic Liquid Reduction and Electrolysis reactors for O_2/metals – MSFC CIF/PPBE22 and SBIR Phase I Faraday Technology
  - Plasma Hydrogen Reduction reactor and reactant control – KSC CIF and PPBE22
  - CO/H_2 Reduction and Metal formulation - SBIR Phase II Sequential with Pioneer Astronautics
  - Carbothermal/Vapor Pyrolysis with Solar Concentrator – SBIR Phase I with Outward
- **Long-life, regolith transfer (100's mT) and low leakage regolith inlet/outlet valves (10,000's cycles)**
  - Fundamental Regolith Properties project – regolith sealing and vibratory regolith transfer – NASA GRC
  - Regolith Valve – NASA GRC
  - Dev of Dust-Tolerant Seals & Performance Database - NASA
- **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
- **Reactant/Product Separation, Regeneration, and Recycling**
  - Helium and Hydrogen Mixed Gas Separator – SBIR with Skyhaven
  - Methane/Hydrogen Microchannel Separator – BAA with Skyhaven
- **Autonomous process monitoring, including measuring mineral properties/oxygen content before and after processing**
  - Laser Spectrometers for Impurity Analysis in ISRU Gas Streams - JPL
- **Water capture, clean-up, quality measurement and electrolysis (10,000's kg/yr)**
  - *See Lunar Polar Ice Mining – Technology Development by Function*

ISRU & Surface Construction Technology Development* (4 of 5)
Excavation

**Impacts due to FY21 Appropriations in work*

- **Excavation and Sample Transfer for Science and ISRU Demonstrations**
  - PlanetVac: pneumatic transfer
  - SAMPLR: Arm/scoop
  - COLDArm: Arm/scoop with instruments

- **Excavation of Hard Regolith/Ice material**
  - Fundamental Regolith Properties Project – regolith/excavation forces
  - Motors for dusty & extremely cold environments; BMG Gears and Motors
  - Lunar Ice Mining Using a Heat-Assisted Cutting Tool – SBIR Phase I w/ Sierra Lobo
  - NASA LSII RASSOR Bucket Drum Design GrabCAD Challenge
  - Break the Ice Centennial Challenge (Soon to be released)

- **Excavation and Delivery of Regolith:** Long-duration operation (100's days) of mechanisms with abrasive regolith and lunar environmental conditions (esp. PSR conditions)
  - Fundamental Regolith Properties Project – regolith/excavation forces
  - Motors for dusty & extremely cold environments; BMG Gears and Motors
  - ISRU Pilot Excavator (RASSOR) to flight prototype
  - Build and Excavation Autonomous System with Transportation BEAST

ISRU & Surface Construction Technology Development* (5 of 5)
Surface Construction

**Impacts due to FY21 Appropriations in work*

- **Surface Construction Materials**
  - Developing a Material Response Model of Biopolymer Stabilized Regolith to Predict Micrometeoriod Damage of ISRU Habitat Systems – STRG with Stanford Univ.
  - Lattice Reinforced Regolith Concrete for Lunar Infrastructure – NASA MSFC
  - In Situ Lunar Launch and Landing Pad Construction with Regolith and Thermoset Polymers – NASA KSC
  - Regolith size sorting and mineral beneficiation - SBIR Phase II Sequential with Pioneer Astronautics
  - Regolith size sorting - SBIR Phase I with Grainflow (not selected for Phase II)

- **Surface Construction Techniques and Applications**
  - ISM-Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) – NASA MSFC
  - In Situ Construction – NASA KSC
  - Lunar Safe Haven Seedling Study – NASA LaRC
  - Additive Construction System for Lunar ISRU Applications – ACO AI Space Factory & KSC
  - Concentrated Solar Regolith Additive Manufacturing – STRG with CSM
  - Collaborative Manipulation for Space Exploration and Construction – STRG with Stanford Univ.
  - Scalable Cellular Infrastructure Technology – NASA

University & Public Involvement
ISRU & Construction Related Challenges

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

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

Watts on the Moon Challenge
- Solutions for energy distribution, management, and/or storage
- Launched Sept. 2020

Break the Ice Challenge
- Excavate icy regolith in PSR
- Phase I launched Nov. 2020

Lunar PSR Challenge 2020 – completed Jan. 2021
- Exploration of PSR regions
- Technologies to support ISRU in PSRs
- Capabilities to explore & operate in PSRs

Lunar PSR Challenge Results
- – 8 university teams; mobility, power beaming, tether, and wireless charging, instrument, and tower
- – Winner: MTU superconducting cable deployment

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

Moon Mars Ice Challenge
- Yearly, university, started in 2017 for Mars ice; added Moon in 2019
- Understand subsurface stratigraphy/hardness
- Extract subsurface water
- 10 teams compete in final 2 day event at LaRC

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

Flight Evolution & Demonstration Strategy

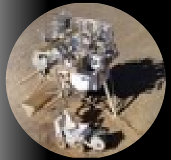
ISRU - Surface Excavation and Construction

Reconnaissance, Prospecting, Sampling | **Resource Acquisition & Processing** | **Pilot Consumable Production**

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

Follow The Natural Resources: Demonstrations of systems for extraction and processing of raw materials for future mission consumables production and storage.

Sustainable Exploration: Scalable Pilot - Systems demonstrating production of consumables from in-situ resources in order to better support sustained human presence.


Oxygen Extraction Ground Demo


Polar Resources Ice Mining Experiment (PRIME-1)

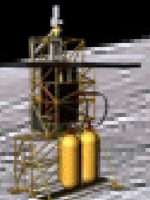

Volatiles Investigating Polar Exploration Rover (VIPER) w/rover


Ice-Mining Demo

Leverages VIPER design - Water extraction via heating regolith; analyze water; Measure volatiles & contaminants


ISRU Pilot Excavator

Lunar Surface Construction Demo 1


O2 Extraction Demo


Lunar Surface Construction Demo (Landing Pad)


Lunar Auger Dryer


ISRU Pilot System for Consumable Production

Early 2020's | *Mid-2020's* | *Late 2020's*

Key Questions to Address to Determine Path

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

Polar Water Mining Path

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

Oxygen from Regolith Path

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

Pilot Plant

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

PRIME-1 & VIPER

First Steps toward surface understanding of Polar Water and Volatiles

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

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

Volatiles Investigation Polar Exploration Rover (VIPER)

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

STMD ISRU Development and Implementation Plan Summary

- STMD is reducing the risk of including ISRU into human Lunar and Mars exploration through a series of demonstrations, leading to mission relevant 'pilot scale' demonstration of ISRU and product demonstration*
  - Breaking the Catch-22 of ISRU not being a 'pull' technology and therefore lower priority in development

- An extensive technology evaluation and gap assessment has been performed to achieve the ISRU architecture insertion plan
  - Moon to Mars synergy
  - Support and enable Space Commercialization

- A full range of ISRU technologies across all TRLs are included in STMD Technology Pipeline

- New lunar ISRU technology projects started in FY20 and planned new starts in FY21*:
  - Polar water/volatile resource assessment
  - Polar water extraction and collection
  - Oxygen extraction from regolith
  - Regolith excavation, preparation, and delivery for O_2 and Water extraction
  - Surface Construction

- A strategy for system engineering, modeling/analysis, integration, and ground environmental of end-to-end ISRU capability testing is in work

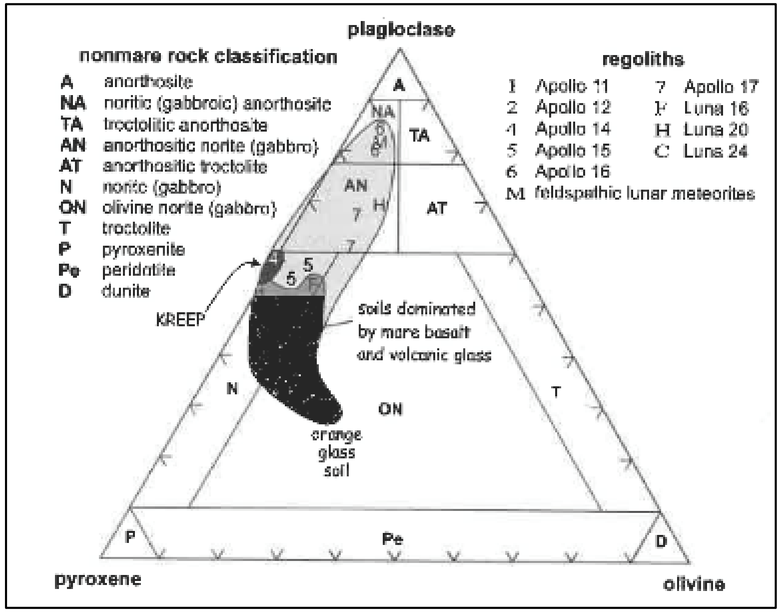
**Impacts due to FY21 Appropriations in work*

Backup

Lunar Resources

Lunar Regolith

- **>40% Oxygen by mass**
  - Silicate minerals make up over 90% of the Moon
- Regolith
  - Mare: Basalt (plagioclase, pyroxene, olivine)
  - Highland/Polar: >75% anorthite, iron poor
- Pyroclastic Glass
- KREEP (Potassium, Rare Earth Elements, Phosphorous)
- Solar Wind Implanted Volatiles

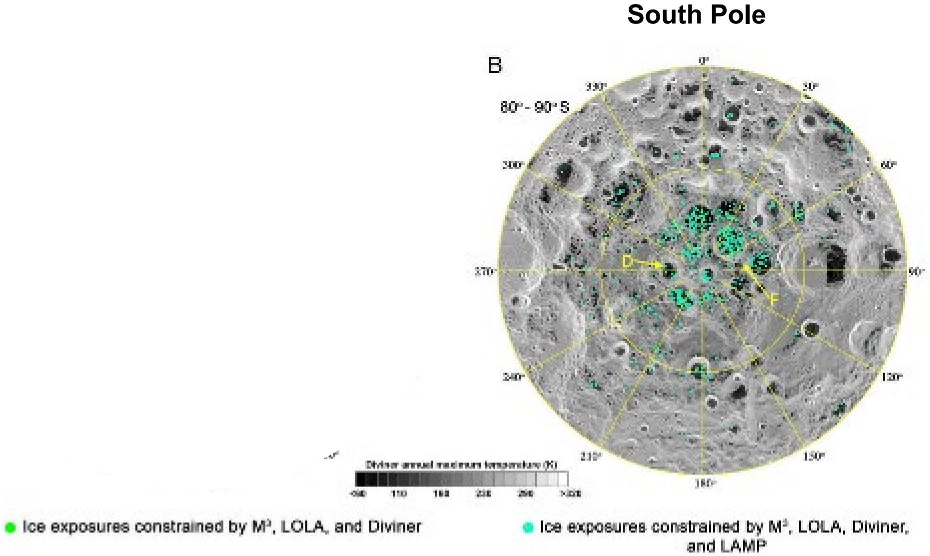


From *New Views of the Moon*

Polar Water/Volatiles

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

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



Li et. al, (2018), *Direct evidence of surface exposed water ice in the lunar polar regions*

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

Table courtesy of Tony Colaprete

STMD LSII Capability Development

Area	Type	Activities
ISRU	**GCD Activities** *(Mid TRL)*	• Polar Resources Ice Mining Experiment-1 (PRIME-1) – *TRL 6+* • Light Water Analysis & Volatile Extraction (Light WAVE) – *TRL 6* • Fundamental Regolith Properties, Handling, and Water Capture – *TRL 5-6* • Tipping Point (TP)-LSII Lunar Ice Processing [OxEon Energy, LLC] – *TRL 5* • Laser In-Situ Resource Analysis (LIRA) – *TRL 6* • Carbothermal Reduction Demonstration – *TRL 6* • Resource Recovery with Ionic Liquid for Exploration (RRILE) – *TRL 4* • Molten Regolith Electrolysis (MRE) – *TRL 6* • Regolith Valve Development – *TRL 6* • Plasma Reduction for Oxygen from Regolith – *TRL 5* • Adv. Alkaline Reversible Cell/Dirty Water – *TRL 6* • Lunar Auger Dryer ISRU (LADI) – *TRL 6* • TP-LSII Lunar Propellant Production Plant (LP3) [Skyre, Inc.] – *TRL 5* • TP-Coupler for Propellant Transfer (CPT) [SpaceX] – *TRL 5* • Lunar Simulant Development • Dirty Lunar Surface Simulation
	BAAs *(Mid TRL)*	• Advanced Alkaline Electolyzer to Support NASA ISRU Applications [Teledyne Energy Systems, Inc.] – *TRL 5* • ISRU-derived Water Purification and Hydrogen Oxygen Production (IHOP) [Paragon Space Development Corp.] – *TRL 5* • ISRU-Water Electrolysis Trade Study [Collins Aerospace] • Production of Oxygen and Fuels from In-Situ Resources on Mars (O2PM) [OxEon Energy LLC] – *TRL 5* • Enhancing Lunar Exploration with ISRU Strategies Study [Blue Origin] • Integrated Architecture Trade Studies on ISRU Technologies for Human Space Exploration [University of Illinois]
	SBIRs *(Low to Mid TRL)*	• Phase II Sequential – Extraterrestrial Metals Processing [Pioneer Astronautics] – *TRL 6* • Phase III - Carbothermal Reduction Reactor Design [Sierra Nevada Corp.] – *TRL 5* • Phase III – Carbothermal Reactor Risk Reduction Testing and Analytical Model Development [Sierra Nevada Corp./Orbitec] – *TRL 3* • Phase II – Redox Tolerant Cathode for Solid Oxide Electrolysis Stacks [OxEon Energy, LLC] – *TRL 5* • Phase II – Helium and Hydrogen Mixed Gas Separator [Skyhaven Systems, LLC] – *TRL 5* • Phase I – Solar Concentrator System for Lunar ISRU Applications [Physical Sciences, Inc.] – *TRL 6* • Phase I (National Science Foundation) – Molten Regolith Electrolysis [Lunar Resources] – *TRL 4*
	NIACs *(Low to Mid TRL)*	• Phase III – Robotic Technologies Enabling the Exploration of Lunar Pits [Carnegie Mellon/Astrobotic Technology, Inc.] – *TRL 5* • Phase I – Lunar Polar Propellant Mining Outpost (LPMO) [TransAstra Corp.] – *TRL 3* • Phase I – Ultra Low Energy Water Extraction [University of Central Florida] – *TRL 3*
	CIFs *(Low TRL)*	• Lunar Regolith Hydrogen Reduction using a Hydrogen Plasma – *TRL 2-3* • Characterization of Lunar Polar Volatiles for Curation and ISRU – *TRL 2*
	ESIs *(Low TRL)*	• Material Characterization while Drilling on Lunar/Martian Surface [Colorado School of Mines] – *TRL 3*
	Challenges *(Low TRL)*	• Ten universities selected as finalists in the 2020 Revolutionary Aerospace Systems Concepts Academic Challenge (RASC-AL) Moon to Mars Ice & Prospecting Challenge – *TRL 2-3*
	STRG *(Low TRL)*	• Upcoming ISRU Lunar Surface Technology Research (LuSTR) – *TRL 2-3*

STMD LSII Capability Development (cont.)

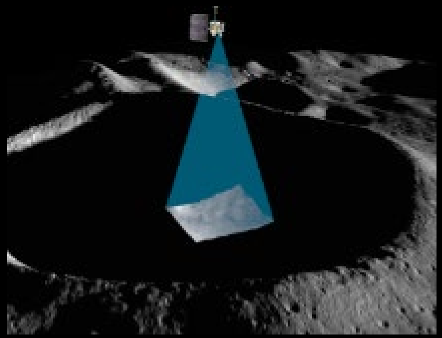
Excavation and Construction	**GCD Activities** ***(Mid TRL)***	• Build and Excavation Autonomous System with Transportation (BEAST) – *TRL 6* • ISRU Pilot Excavator – *TRL 6* • ISM-Moon-to-Mars Planetary Autonomous Construction Technology (MMPACT) – *TRL 6* *(Microwave Manufacturing)* • In-Situ Construction – *TRL 6* • Lunar Safe Haven Seedling Study • Additive Construction System for Lunar ISRU Application – *TRL 6*
	CIFs ***(Low to Mid TRL)***	• Scalable Cellular Infrastructure Technology (SCI-Tech) – *TRL 5* • Lattice Reinforced Regolith Concrete for Lunar Infrastructure – *TRL 2* • In-Situ Lunar Launch and Landing Pad Construction with Regolith and Thermoset Polymers – *TRL 2-3*
	STRG ***(Low TRL)***	• Developing a Material Response Model of Biopolymer-Stabilized Regolith to Predict Micrometeoroid Damage of ISRU Habitat Systems [Stanford University] – *TRL 3* • Concentrated Solar Regolith Additive Manufacturing [Colorado School of Mines] – *TRL 3* • Collaborative Manipulation for Space Exploration and Construction [Stanford University] – *TRL 3*
	Crowd-Sourcing Challenge ***(Low TRL)***	• NASA LSII Regolith Advanced Surface Systems Operations Robot (RASSOR) Bucket Drum Design GrabCAD Challenge – *TRL 2-3*
	Centennial Challenge ***(Low TRL)***	• Upcoming Surface Excavation Challenge – *TRL 2-3*
	Yet2 Market/ Technology Search	• Lunar Surface Manufacturing

Lunar Science & Resource Assessment

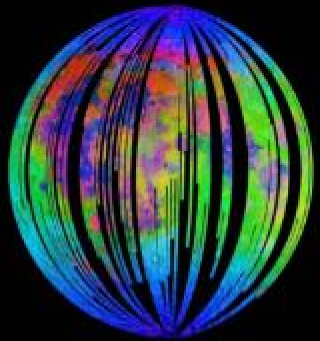
Orbital Missions

Lunar Reconnaissance Orbiter

ShadowCam on Korean Pathfinder Lunar Orbiter

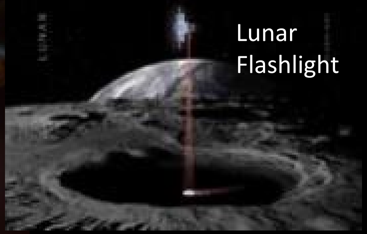


Lunar Trailblazer



Lunar IceCube

Lunar Flashlight



LunaH-Map

Surface Missions

Astrobotics

Intuitive Machines

Masten

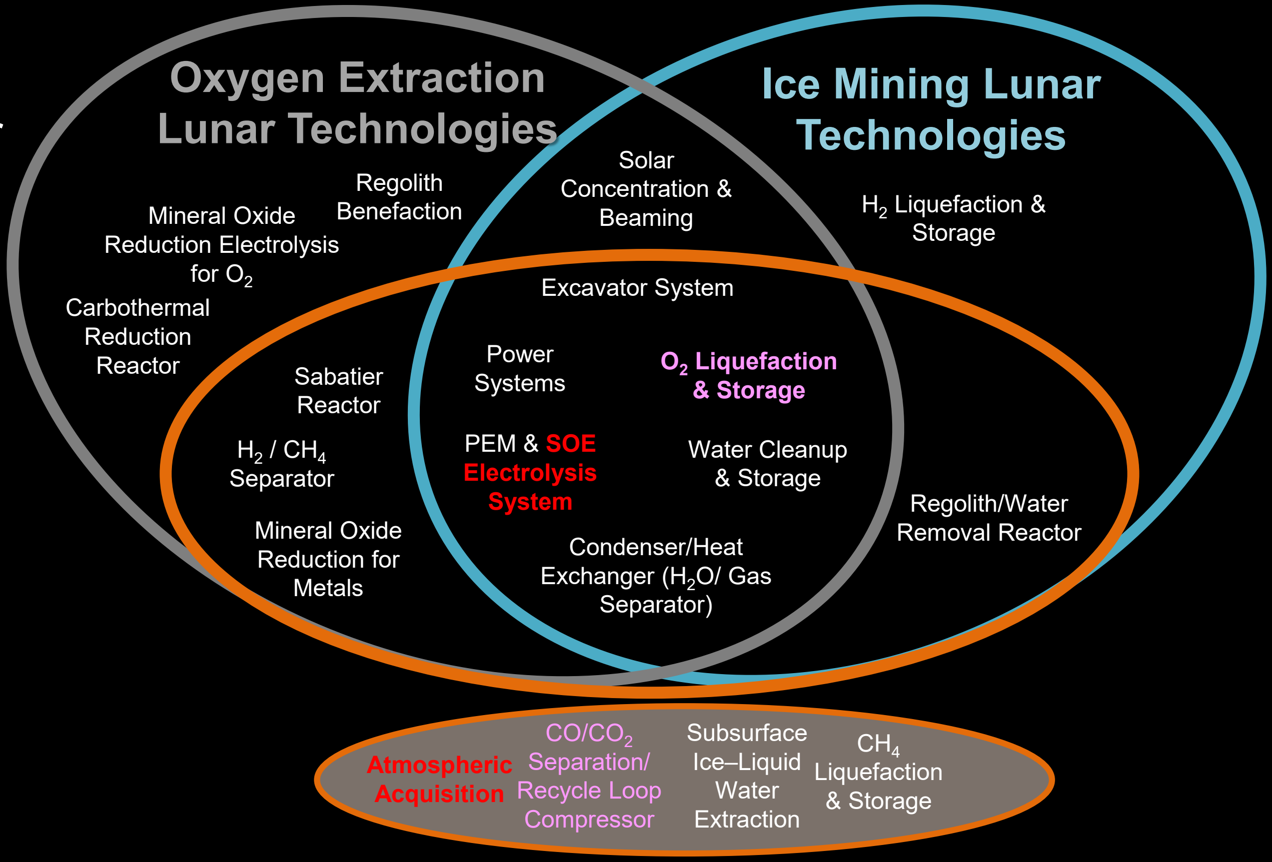
PRIME-1

VIPER

Moon-to-Mars Mars Surface Tech Development – Live

With proper attention to production rates, modularization, and interfaces, similar subsystem modules and excavators can be utilized on both Moon and Mars missions.

- The LSII portfolio includes ice-mining and oxygen extraction technologies and demonstrations for key lunar surface technologies that are also Mars-forward:
  - Sabatier/CO_2 conversion to Methane
  - PEM Water Electrolysis and Solid Oxide Water Electrolysis
  - Water cleanup/contaminant removal
  - Soil/regolith excavation, preparation, and delivery
- Current LSII Mars-Unique Surface Component and Sub-system Technologies Under Development:
  - Atmospheric Acquisition and CO/CO_2 Separation/Recycle Loop Compressor technologies
  - Subsurface Ice-Liquid Water Extraction technologies
  - CH_4 Liquefaction & Storage technologies
  - Large-scale dust mitigation technologies



Mars-unique Technologies
Note: System-level demonstrations not included in this budget request)

Outcomes from LSIC ISRU Supply/Demand Workshop

Major Takeaways

- There is a real, and near term (less than a decade) potential for a commercial market for liquid oxygen (LOX) and water sourced from the Moon. Commercial demand ranges from tens to hundreds of metric tonnes a year
  - Dynetics/Blue Origin ~30 tonnes per year. SpaceX, 100s of tonnes per year
  - LOx will be >~75% of the demand my mass and can be obtained from dry regolith
- Demand for metals, and silicon will quickly follow.
- NASA and DOD can and may need to serve as anchor customers to ensure initial viability for this new marketplace
- In order to most rapidly achieve the projected need in propellent production, significant and rapid technology development and demonstration is required
- Major outstanding questions are not over quantities or types of products, but issues such as timelines, purity requirements, delivery locations, etc.

Recommendations

- NASA Being an anchor customer through competitive contracts to purchase the resource at quantity
- NASA can support maturation of technology by flying a demonstration unit, a pilot plant, and potentially a full production plant.
- NASA can supporting O_2 from regolith extraction technologies without reservations
- Continuing development of water harvesting technologies, and surveying to characterize the form and distribution of the water deposits
- Communicate with the community through LSIC to coordinate standards definition.

What are the Barriers to Commercial ISRU?

Today: There is Neither a Production Capability or Market

Barriers	What Can/Should Be Done?
Resource Uncertainty − Resource Exploration − Reserve Estimation	▪ Increase global resolution of resource information ▪ Campaign of resource exploration missions (Gov. & Industry) ▪ Agreement/standards for reserve estimation (ex JORC/NI43-101)
Mining Technology Readiness − Demonstrated Scale − Demonstrated Operations	▪ Government/industry partnerships & space mining institute ▪ Spin-in/Spin-off Technologies into Terrestrial Applications − Incentives for insertion; greener/safer innovations ▪ Demonstrate technologies, production rate, and product quality
Customers − Known users/market − Market growth potential	▪ Terrestrial market use of technology/capability ▪ Demonstrate product usage ▪ Develop space transportation & infrastructure growth around ISRU ▪ Gov. as anchor tenant once demand has been established ▪ Enable bootstrapping through stepwise incentives
Sustainable Operations − Reliable/Cheap Transportation − Logistics and Maintenance − Infrastructure	▪ Utilize additive manufacturing for high wear parts ▪ Governments help establish initial transportation, power, communication, and surface infrastructure ▪ Establish common interfacing standards
Regulatory − Legal Framework − Product/Property Rights − Standards − Taxes	▪ Establish international agreements **(Artemis Accords)** ▪ Establish stable legal and regulatory framework ▪ Establish tax incentives/flow-through shares ▪ Enable ownership enforcement