Lunar ISRU Development and Flight Strategy

Presentation to Lunar Surface Innovation Consortium

July 15, 2020

NASA Lunar ISRU Purpose

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)
- ***SPD-2: Streamlining Regulations on the Commercial Use of Space***
  - Promote economic growth and encourage American leadership in space commerce

Why Use Space Resources for Human Exploration

- **Using Space Resources can reduce mission and architecture mass and costs**
  - Launch mass savings
  - Reduce launch numbers
  - Reduce costs - reuse mission transportation assets
  - Supports terrestrial industry/Enables space commercialization

- **Using Space Resources can increase safety for crew and mission success**
  - Ensure and enhance crew safety
  - Provide critical solutions for mission assurance
  - Minimizes impact of shortfalls in other system performance
  - 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**

How Making Propellants on Planetary Surfaces Saves on Launches and Cost (Gear Ratio Effect)

Every 1 kg of propellant made on the Moon or Mars saves 7.5 to 11.2 kg in LEO

Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

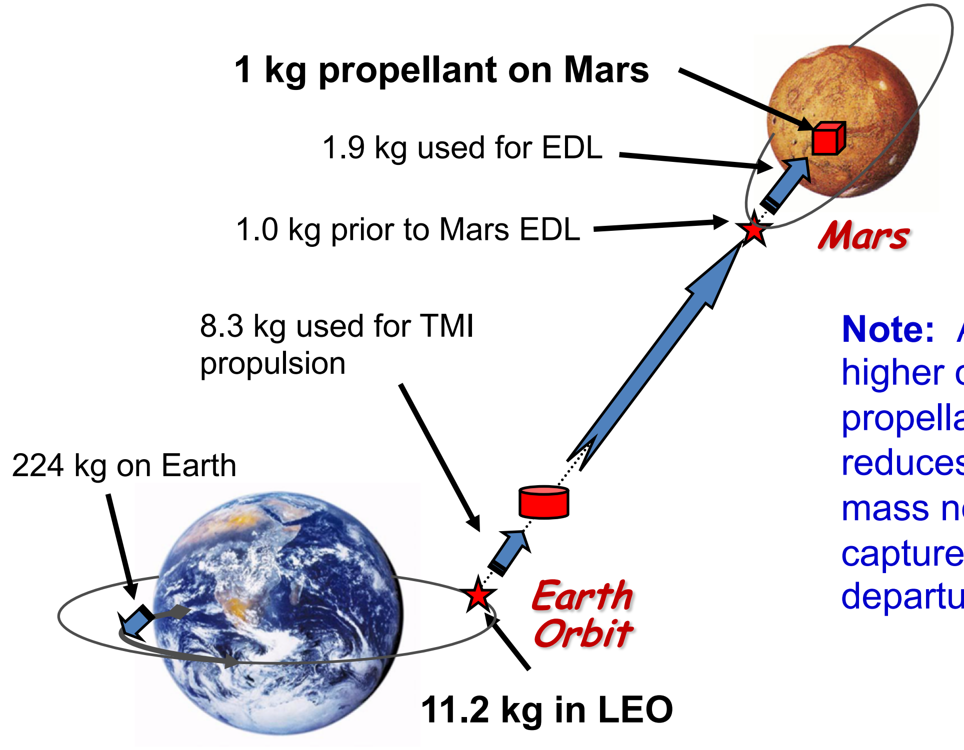
- Savings depend on in-space transportation approach and assumptions; previous Mars gear ratio calculations showed only a 7.5 kg saving
- 25,000 kg mass savings from propellant production on Mars for ascent = 187,500 to 282,500 kg launched into LEO

Mars Crew Ascent Mission

− Oxygen only	75% of ascent prop. mass:	20 to 23 mT
− Methane + Oxygen	100% of ascent prop. mass:	25.7 to 29.6 mT

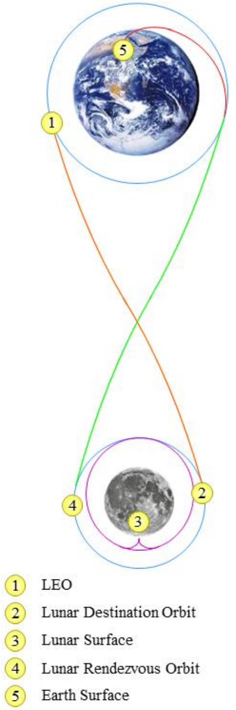
Moon Lander: Surface to NRHO

- Crew Ascent Stage (1 way): 3 to 6 mT O_2
- Single Stage (both ways): 40 to 50 mT O_2/H_2



Note: Ascent to higher orbit with ISRU propellant also reduces propellant mass needed for orbit capture (TLI/TMI) and departure burns (TEI)

Estimates based on Aerocapture at Mars

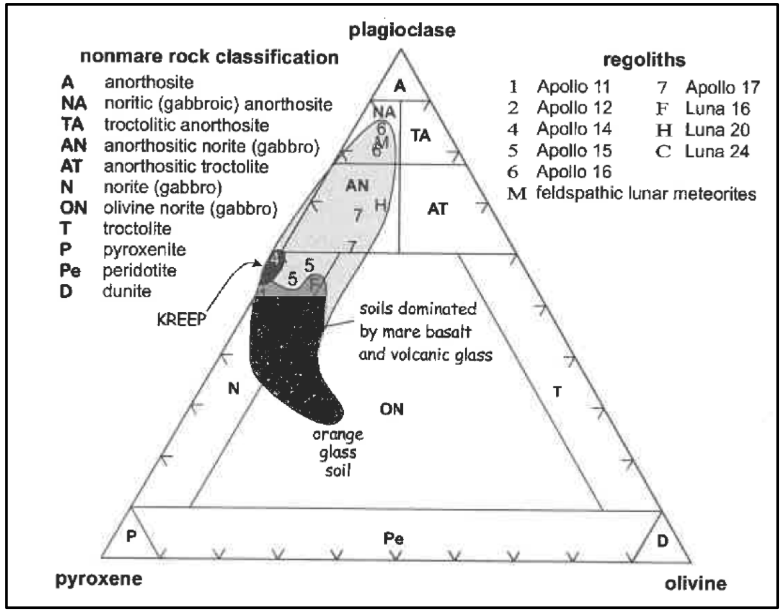


A Kilogram of Mass Delivered Here…	…Adds This Much Initial Architecture Mass in LEO	…Adds This Much To the Launch Pad Mass
Ground to LEO	-	20.4 kg
LEO to Lunar Orbit (#1→#2)	4.3 kg	87.7 kg
LEO to Lunar Surface (#1→#3; e.g., Descent Stage)	7.5 kg	153 kg
LEO to Lunar Orbit to Earth Surface (#1→#4→#5; e.g., 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

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

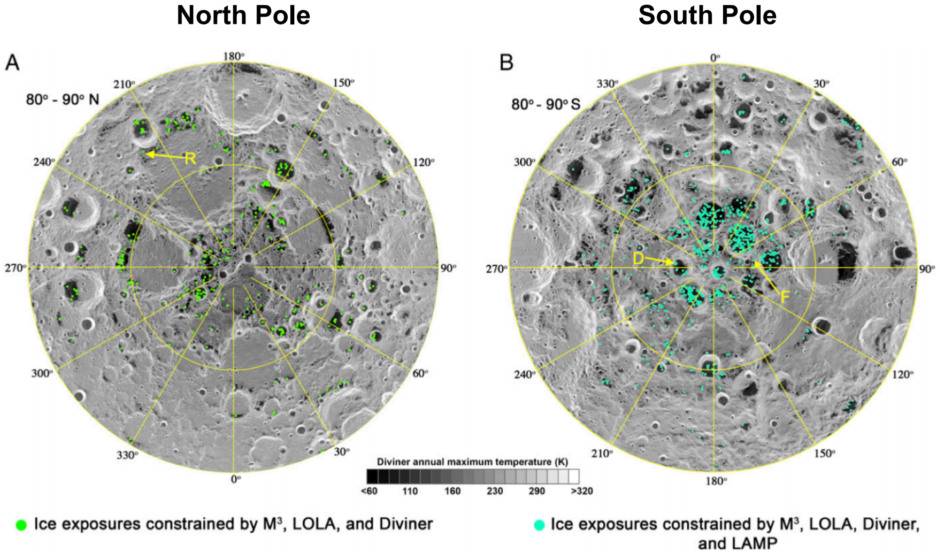


From *New Views of the Moon*

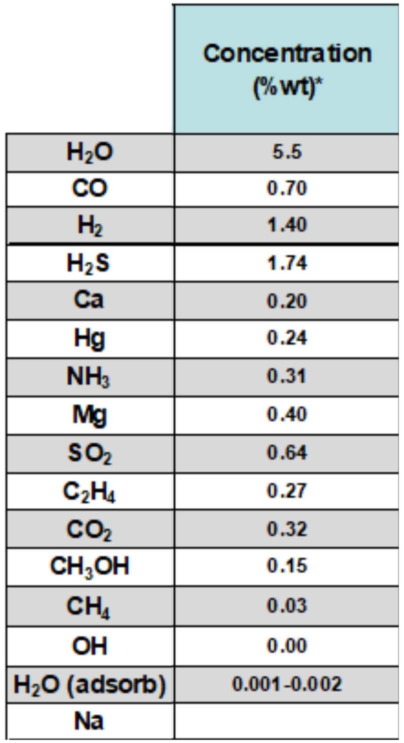
Polar Water/Volatiles

- 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*



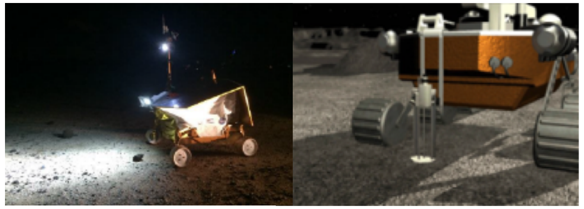
	Concentration (%wt)*
H_2O	5.5
CO	0.70
H_2	1.40
H_2S	1.74
Ca	0.20
Hg	0.24
NH_3	0.31
Mg	0.40
SO_2	0.64
C_2H_4	0.27
CO_2	0.32
CH_3OH	0.15
CH_4	0.03
OH	0.00
H_2O (adsorb)	0.001-0.002
Na	

Table courtesy of Tony Colaprete

Lunar Surface ISRU Capabilities

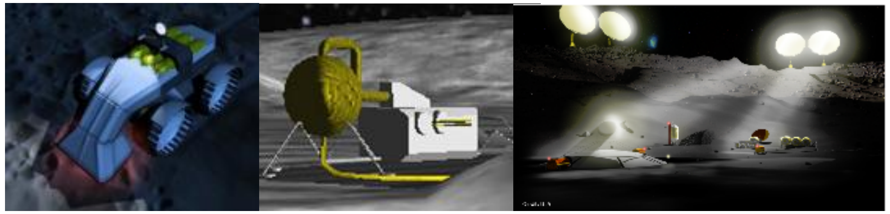
Resource Assessment – Looking for Water/Minerals

Global Assessment

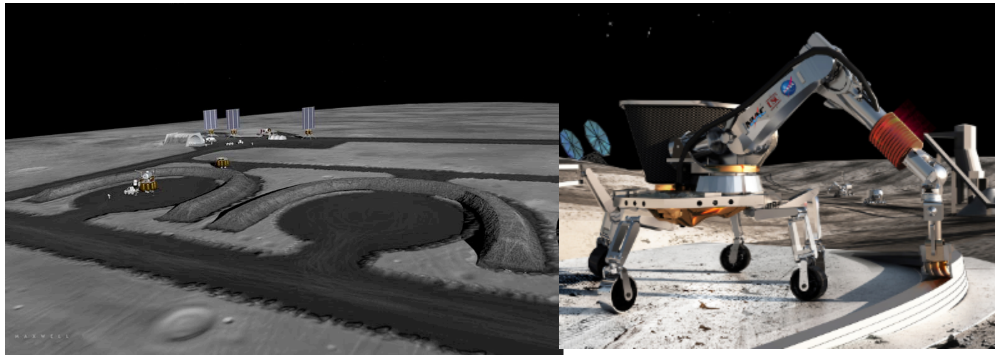


Local Assessment

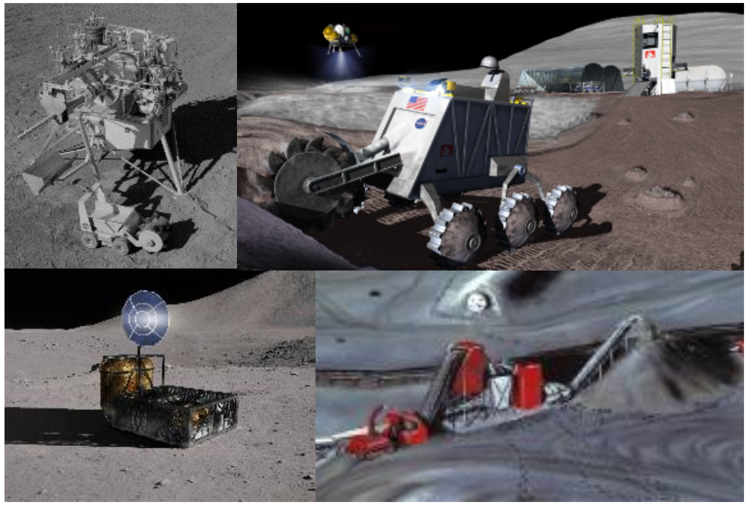
Mining Polar Water & Volatiles



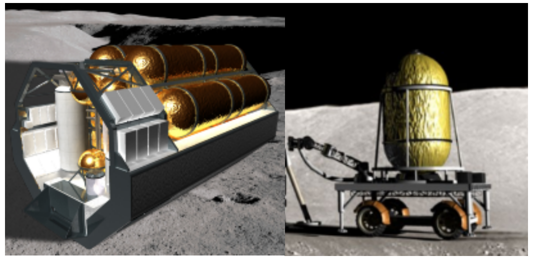
Landing Pads, Berms, Roads, Shielding and Structure Construction



Excavation & Regolith Processing for O_2 & Metal Production



Consumable Storage & Delivery



Consumable Users

Lunar ISRU Mission Consumables:
Polar Water and Oxygen from Regolith

- **Water (and Volatiles) from Polar Regolith**
  - Form, concentration, and distribution of Water in shadowed regions/craters is not known
    - Technologies & missions in work to locate and characterize resources to reduce risk for mission incorporation
  - Provides 100% of chemical propulsion propellant mass
  - Polar water is “Game Changing” and enables long-term sustainability
    - Strongly influences design and reuse of cargo and human landers and transportation elements
    - Strongly influences location for sustained surface operations

- **Oxygen from Regolith**
  - Lunar regolith is >40% oxygen (O_2) by mass
  - Technologies and operations are moderate risk from past work and can be performed anywhere on the Moon
  - Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth); O_2 for EVA, rovers, Habs.
  - Experience from regolith excavation, beneficiation, and transfer applicable to mining Mars hydrated soil/minerals for water and *in situ* manufacturing and constructions

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

In Situ Propellant & Consumable Production (ISPCP) Phases of Evolution and Use

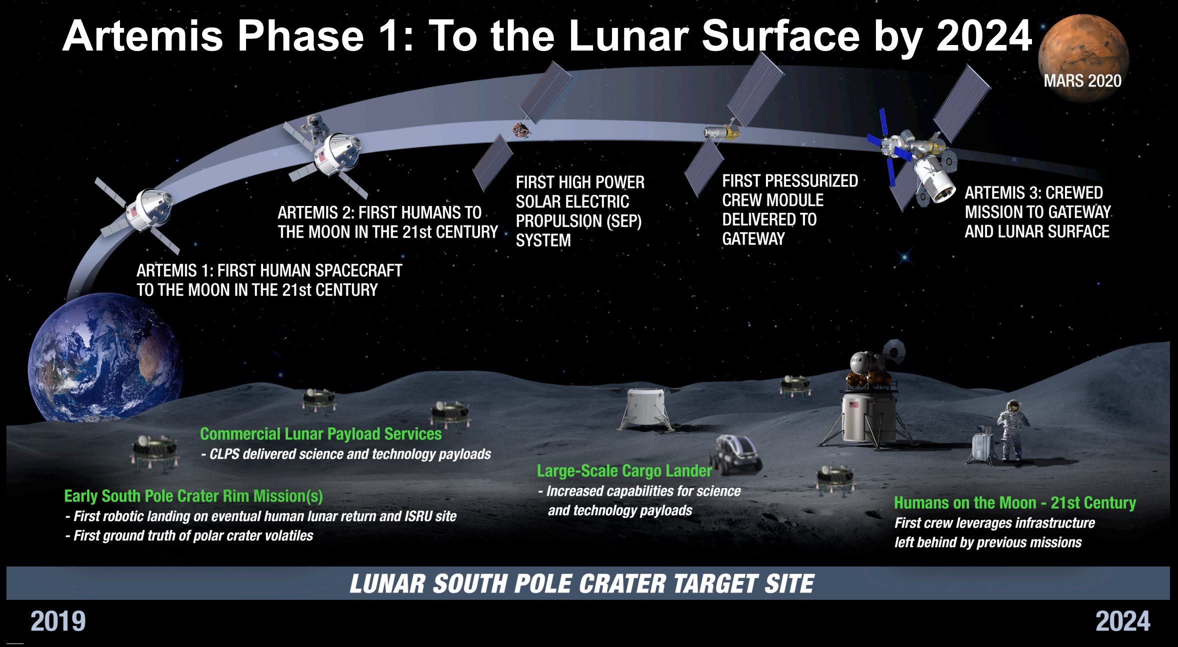
	Demo Scale	Pilot Plant	Crewed Ascent Vehicle*	Full Descent Stage*	Single Stage to NRHO**	Human Mars Transportation^{t}	Commercial Cis-Lunar Transportation$^{\wedge}$
			3 Stage Arch to NRHO				
Timeframe	days to months	6 mo - 1 year	1 mission/yr	1 mission/yr	1 mission/yr	per year	per year
Demo/System Mass$^{\wedge\wedge}$	10's kg to low 100's kg		1400 to 2200 kg	2400 to 3700 kg	Not Defined	Not Defined	29,000 to 41,000 kg
Amount O_2	10's kg	100's to low 1000's kg	4,000 to 6,000 kg	8,000 to 10,000 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	10's to low 100's kg		1,400 to 1,900 kg	5,500 to 9,100 kg	23,000 to 33,000 kg	50,000 to 275,000 kg
Power for O_2 in NPS			20 to 32 KW	40 to 55 KW	N/A	N/A	N/A
Power for H_2O in PSR				21.5 KW	14 to 23 KW		150 to 800 KW
Power for H_2O to O_2/H_2 in NPS				37.5 KWe	55 to 100 KWe		370 to 2,000 KWe

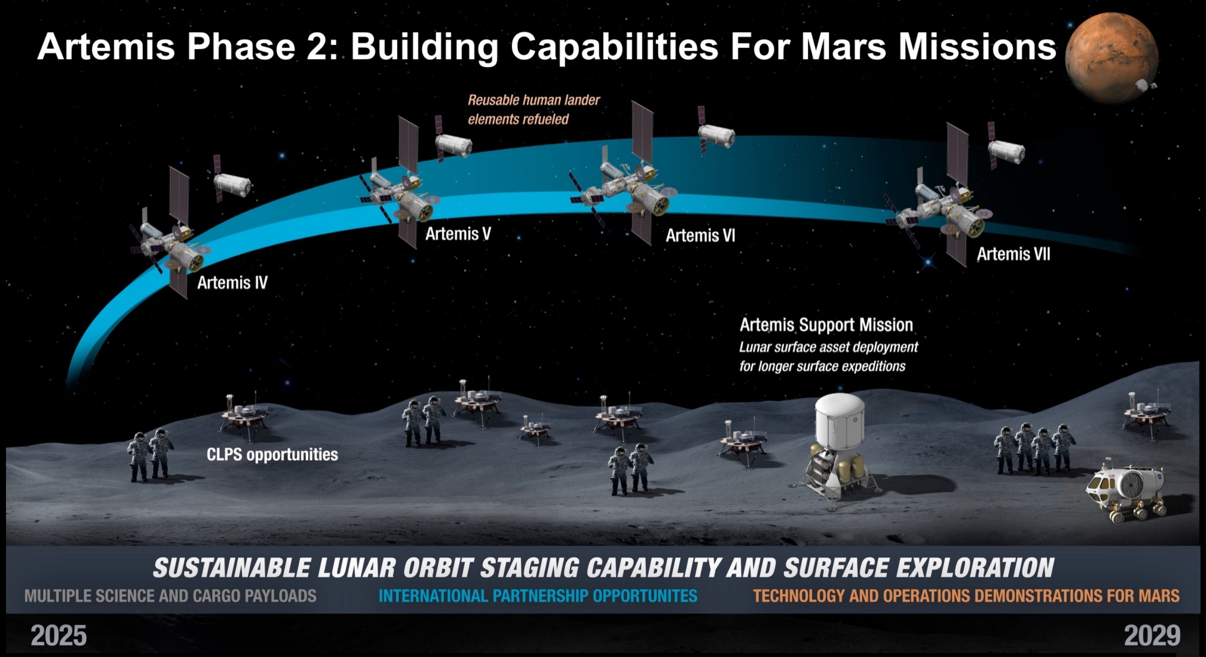
NPR = Near Permanent Sunlight

PSR = Permanently Shadowed Region

- Table use 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

Artemis: Human Lunar Exploration





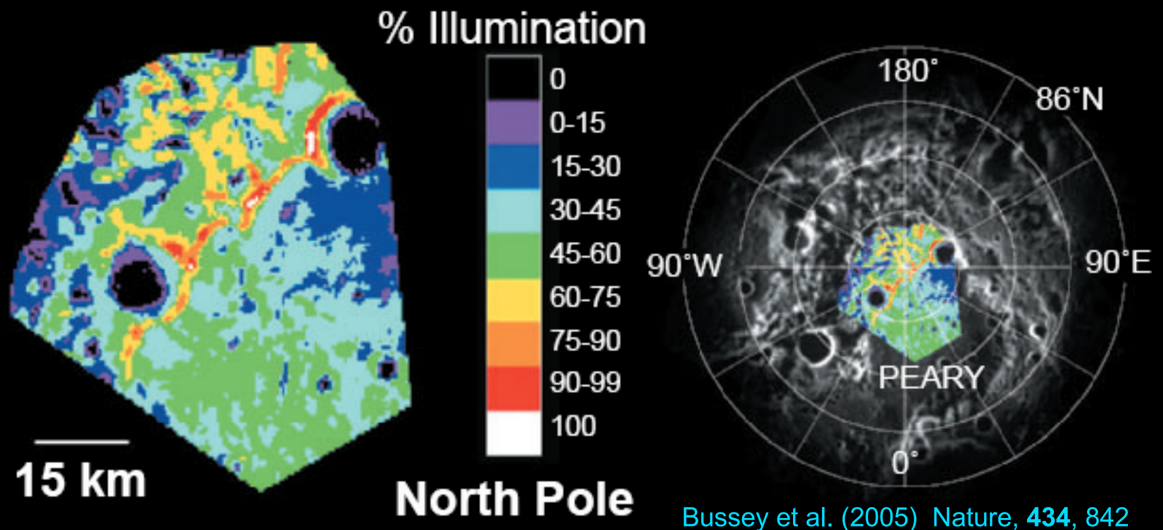
- Pre-2024 – CLPS, Robotic Science and Resource Prospecting
  - Robotic Science
  - Resource Prospecting

- 2024 (-2025) Human Lunar Surface Return
  - Unpressurized Mobility
  - EVA
  - Robotically Pre-deployed science tools and experiments
  - Non-Crewed surface mission robotic operations
    - Science, maintenance and inspection, site survey

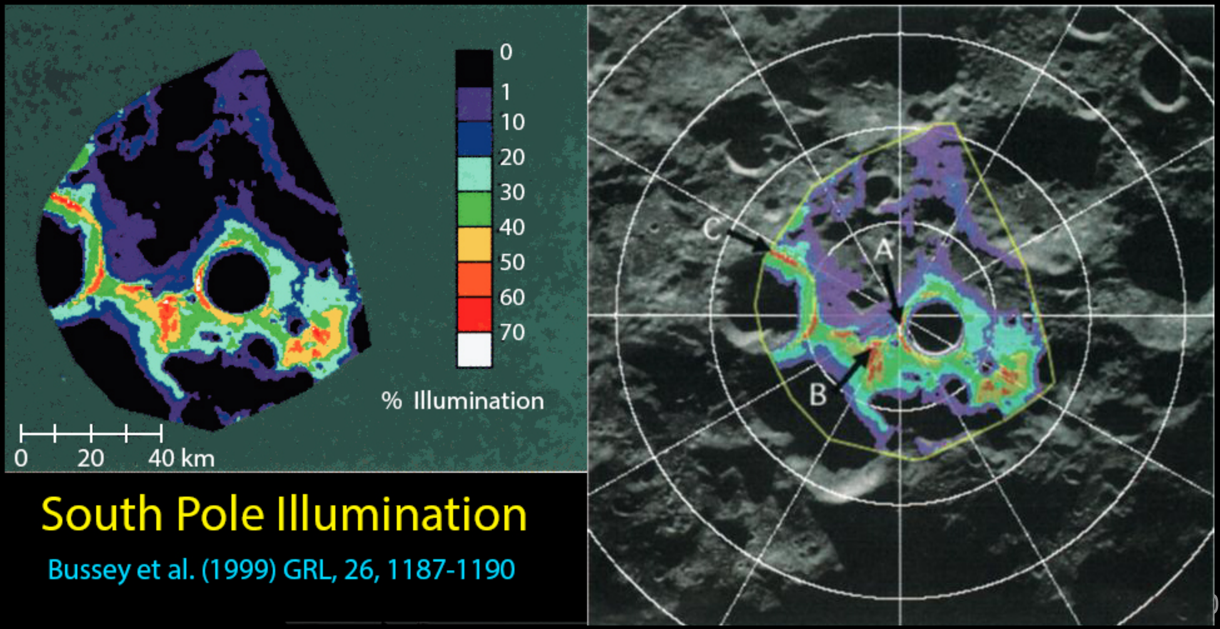
- 2026+ Lunar Mars Mission Analogs and Long-Term Human Lunar Surface Presence
  - Pressurized Mobility
  - Offloading and deployment
  - Pilot scale ISRU
    - Demonstrate use of ISRU
  - Surface Power System
  - Habitat

NASA Artemis is Focused on the Lunar South Pole

"Peaks of Eternal Light" and "Permanently Shadowed Regions" exist on the lunar poles



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



South Pole Illumination

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

Provided by Jennifer Edmunson

Resource Assessment:
What is Needed Before Polar Water Mining Can Occur

- **Reconnaissance/Exploratory Evaluation**: **Evaluation of a larger number of potential PSR resource locations**
  - Better understanding of water deposition & theories, geological context, and orbital data verification/usage
  - Better landing site selection for subsequent prospecting and ice mining demonstration missions

- **Focused Exploratory**: **Evaluation to verify that the model has predicted a potential reserve site.**
  - Water subsurface distribution: 1 m depth target is estimated limit for ISRU systems. Greater depths do not trade well with current technology approaches
  - Vertical distribution resolution of 20 cm based on ISRU excavation techniques and water distribution models requiring 4 measurements over depth
  - Water subsurface abundance >1 % detection limit:
  - Determination of water abundances at 50% accuracy or better

- **Reserve Mapping**: **Obtain broader set of data needed to plan mining con-ops, hardware emplacement, etc**
  - Collect critical information to determine if polar water mining is economical (investment in hardware, infrastructure, and operations vs product and usage)
    - Extensive and thorough assessment of the surface/subsurface water/volatile resources over an extended area (1 km x 1 km min.)
    - Build 3-D interpretation of resource data as it is collected; utilize to redirect traverse and data sampling activities and define ‘minable’ resource locations
  - ISRU Reserve is likely in a PSR, so this asset must survive extended periods in this extreme environment. It is an opportunity to demonstrate technologies also needed for ISRU plant.
  - Reduces risks for technologies and operations associated with polar water mining

ISRU Lunar Development and Demonstration Timeline

Reconnaissance, Prospecting, Sampling

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

Resource Acquisition & Processing

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

Pilot Consumable Production

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

CLPS Drill
Down Select

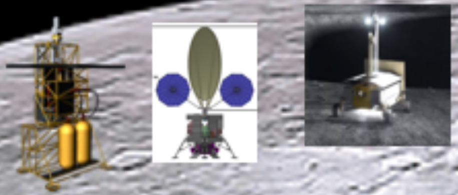
High-fidelity
Simulant
Production

Oxygen from
Lunar Simulant
Ground Demos

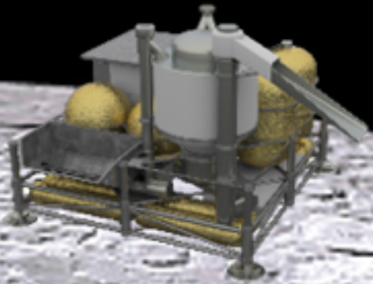
Polar Resources Ice
Mining Experiment
(Prime-1) on CLPS

Volatiles Investigation
Polar Exploration Rover
(VIPER)

ISRU Subsystem
Consumables Extraction
Demos



Scalable Pilot - ISRU
Systems for Consumable
Production



2019

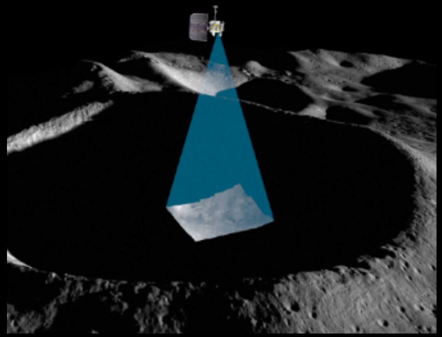
203x

Lunar Science & Resource Prospecting

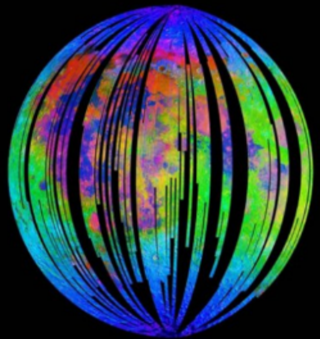
Orbital Missions

Lunar Reconnaissance Orbiter

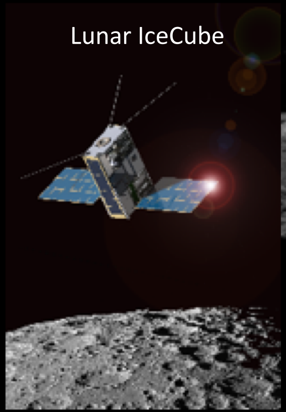
ShadowCam on Korean Pathfinder Lunar Orbiter



Lunar Trailblazer
(Phase A)



Lunar IceCube



Lunar
Flashlight

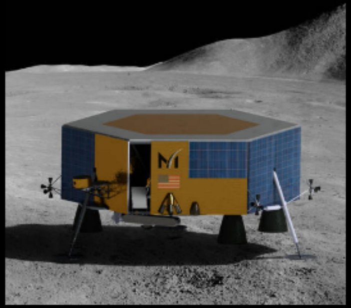
LunaH-Map

Surface Missions

Astrobotics

Intuitive
Machines

Masten



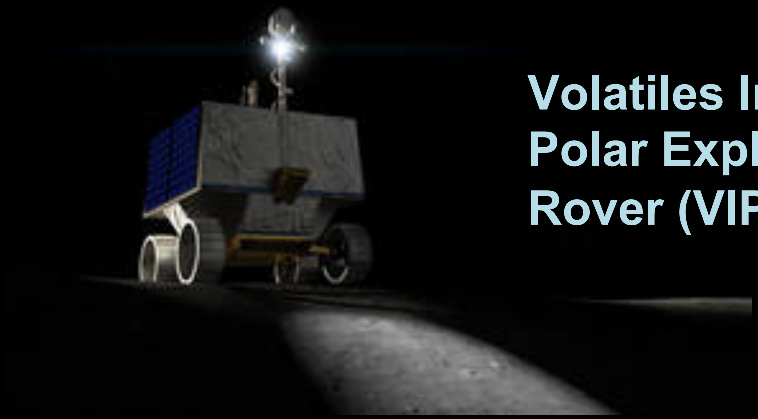
PRIME-1

VIPER

PRIME-1 & VIPER

First Steps toward surface understanding of Polar Water and Volatiles

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



Volatiles Investigation Polar Exploration Rover (VIPER)

- CLPS mounted payload to detect volatiles at 1-m depth in 2022
- Instruments include:
  - Near InfraRed Volatiles Spectrometer System (NIRVSS)
  - Mass Spectrometer Observing Lunar Operations (MSolo)
  - The Regolith and Ice Drill for Exploring New Terrain (TRIDENT)

➡

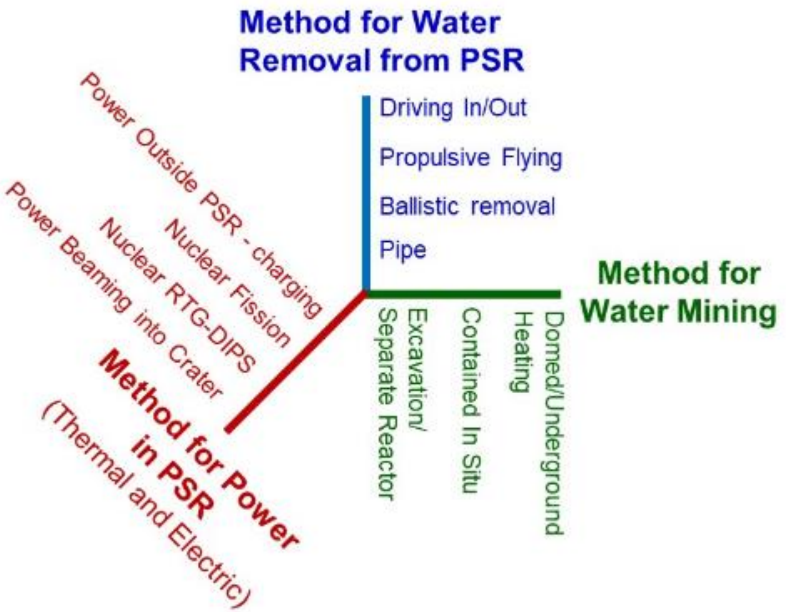
- Dec. 2023 mid-lunar day at South Pole
- Measure volatiles at the lunar poles and acquire new key data on lateral and vertical distribution
  - Neutron Spectrometer System (NSS)
  - NIRVSS IR Spec
  - Msolo Mass Spec
  - TRIDENT Drill
- Build lunar resource maps for future exploration sites
  - Long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

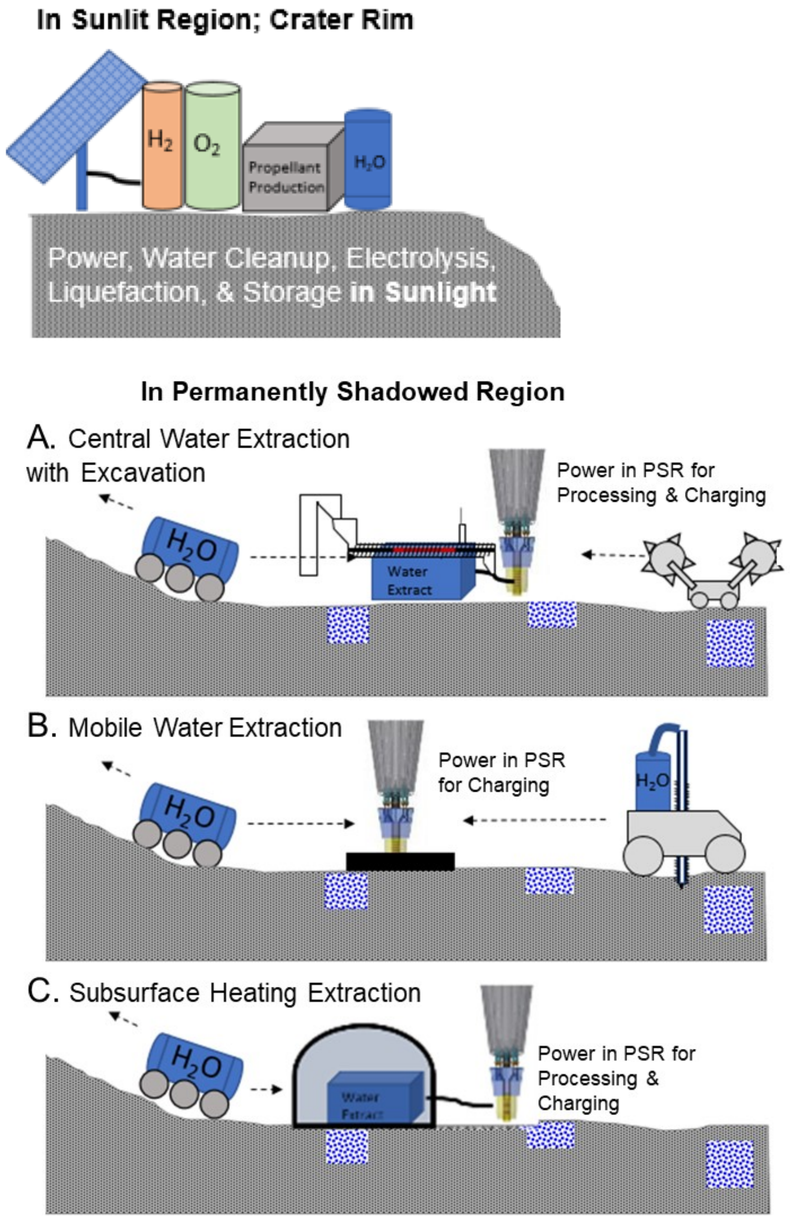
Mining Polar Water: Overview

- **Three main drivers for Water Mining Architecture viability**
  - Method of Water removal from Crater
  - Method of Power in 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.

Preliminary Assessment

Concepts	Architecture Option			Status	Resource Depth access	Spatial Resource definition	Volatiles retention	Material Handling
	IRSU plant	Mobile	In-situ					
Auger Dryer	X			Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Microwave Vessel	X	?		Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Microwave Zamboni		X	X	Concept Study	Surface	10s of Meters	Low	Low
Vibrating Tray	X	X		Breadboard Laboratory hardware	Moderate (cm)	10s of Meters	Low-moderate	High
Coring Auger		X	X	Breadboard Laboratory hardware	Deep (m)	Meters	High	Moderate
Heated Dome			X	Concept Study	Surface	Meter	High	Low
Heated batch (Resolve EBU)	X	?		Field demonstrations	Moderate (cm)	10s of Meters	Low-moderate	High
Water jet/Dome			X	Concept Study	Moderate (cm)	Meter	High	Low

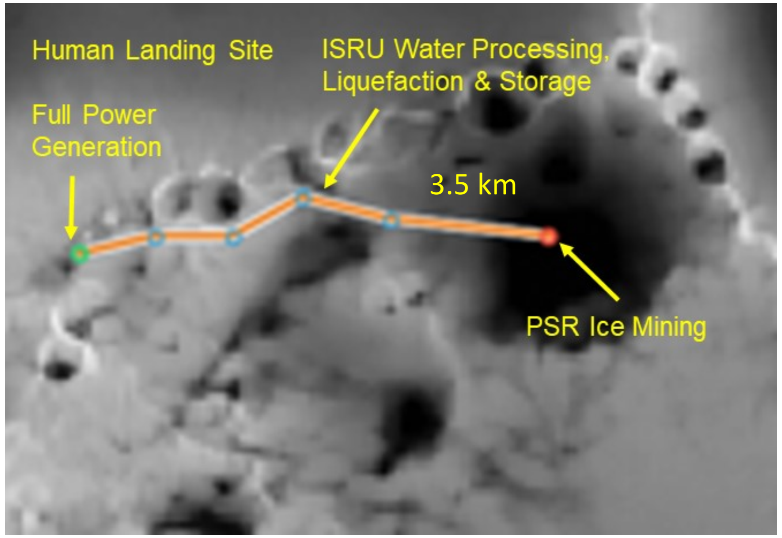




Mining Polar Water: Initial Production Plant Concept

- **Five Systems for Lunar Ice Mining**
  1. Ridge ISRU: Water transfer, cleaning, storage, and electrolysis, and water tankers
  2. Ridge Cryo: Stationary O_2/H_2 liquefaction and storage, transfer, mobile O_2/H_2 tankers
  3. Ridge ISRU Power : Solar array, regenerative fuel cell (nuclear reactor is optional)
  4. PSR ISRU: excavator(s), regolith processing to extract water, water collection/capture, water transfer
  5. PSR Power: ~13 KW
     - Nuclear reactor & power cart/cable (1.5 km) in PSR
     - Power transfer from Ridge ISRU Power System via power cart/cable (5 km) or power beaming

- **Nominal Mission**
  - 15,300 kg water / year (225 days continuous); 13,600 / 1700 kg (O_2/H_2)
    - H_2 production is the driver for O_2/H_2 propulsion systems
  - Water source: 5% water ice particles mixed and frozen in with regolith, underneath a 20 cm desiccated layer
  - Water transported from PSR to Ridge-based plant via water tanker tbd (>20) times per year
  - Nom. traverse path <15 deg. slopes between Ridge and PSR ISRU Systems



Site selected for Ice Mining Study Only

Oxygen Extraction: Overview

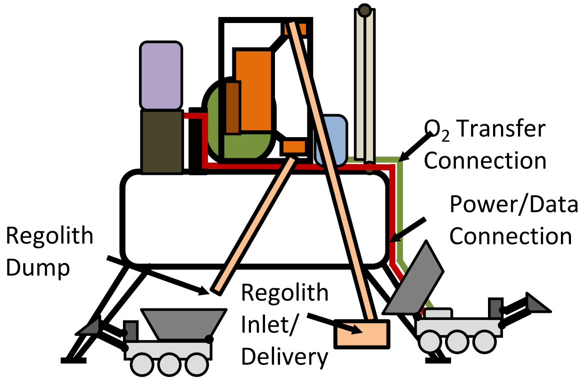
- **Over 20 processes have been identified to extract oxygen from regolith**
  - Components required range from TRL 3 to TRL 9
  - Typically, as processing temps increase, O_2 yield increases, and technical and engineering challenges increase
- **Constellation Program focused on three processes**
  1. Hydrogen (H_2) reduction – System to TRL 4-5 with Analog test in 2008
  2. Carbothermal (CH_4) reduction – System to TRL 4-5 with Analog test in 2010
  3. Molten regolith electrolysis (MRE) – TRL 3
- **NASA/NSF pursuing several processes for Artemis**
  - Carbothermal (SNC and Pioneer), Plasma H_2 Reduction (KSC), MRE (KSC and Lunar Resources), Ionic Liquids (MSFC, SBIR), Vapor Pyrolysis (SBIR)

Preliminary Assessment

	O_2 Extraction			
	H_2 Reduction	**CH_4 Reduction**	**Molten Oxide Electrolysis**	**Ionic Liquid Reduction**
Resource Knowledge	Good - Orbital High Resolution & Apollo Samples			
Site Specificity	Moderate to High (Ilminite & Pyroclastic Glasses Preferred)	Low to Moderate (Iron oxides and Silicates)		
Temperature to Extract	Moderate (900 C)	High (>1600 C)	High (>1600 C)	Low (100+ C)
Energy per Kilogram	High	Moderate	Moderate	?
Extraction Efficiency wt%*	1 to 5	5 to 15	20 to 40	?
TRL	4-5	4-5	3+	2-3
Mars Forward	Moderate	High	Low	Low

*kg O_2/kg bulk regolith

- **Focus on lunar polar region**
  - Highland regolith and long duration sunlight



ConOps for Carbothermal Reduction

① Regolith delivered is analyzed for mineral type and quantity and fed into size sorting and mineral beneficiation unit (if required)

② Regolith in inlet hopper fed into O_2 Reaction Reactor and processed

③ Reactant and product gases are monitored and controlled

④ Any water produced is condensed and analyzed for contaminants

⑤ Water is cleaned and sent to clean water storage tank

⑥ Clean water is transferred to Water Processing Unit and electrolyzed into O_2 and H_2
- O_2 is measured for contaminants and transferred to O_2 Storage Unit

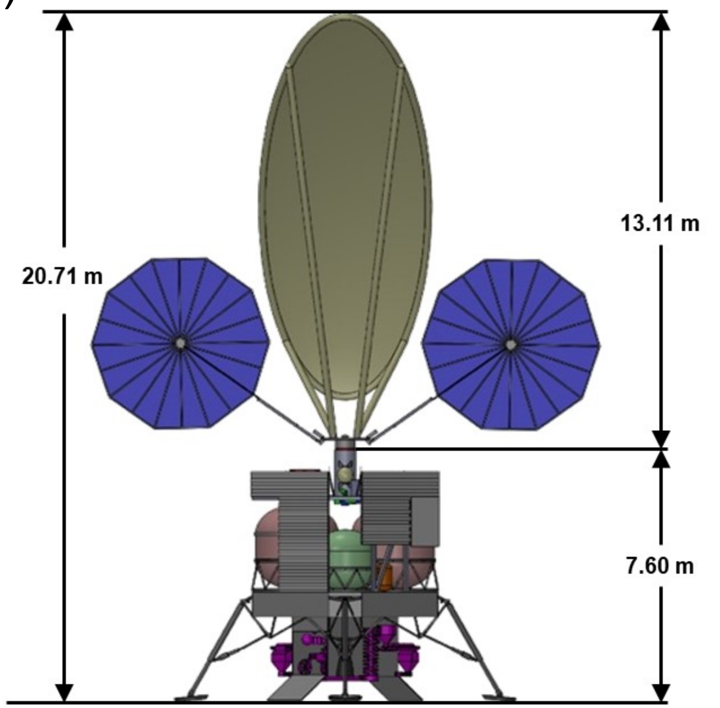
⑦ O_2 Storage unit dries, liquefies, and stores O_2

⑧ Processed regolith is discharged to outlet hopper to cool and be analyzed for change in mineral properties

⑨ Processed regolith discharged from outlet hopper to rover

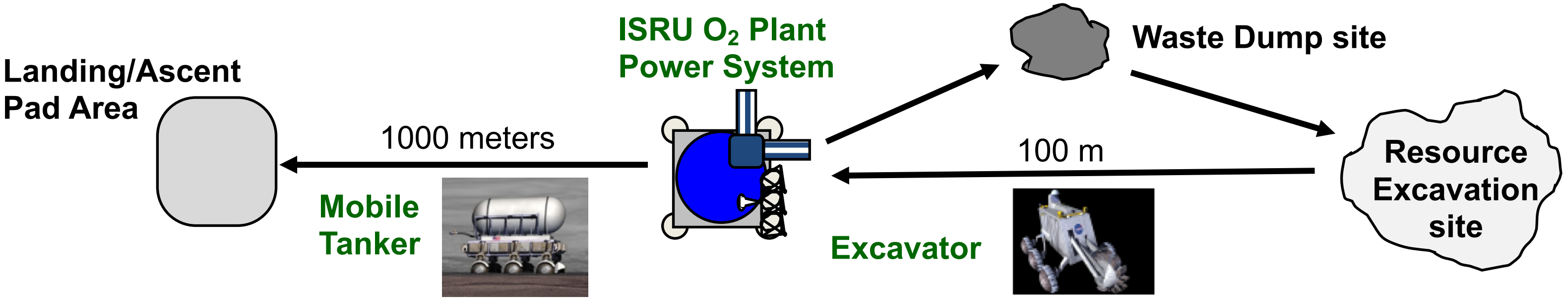
Oxygen Extraction: Initial Production Plant Concept

- **Four Systems for Lunar Ice Mining**
  1. Regolith Excavation/Delivery: excavators, regolith pre-processing (size/mineral sorting), delivery, transfer
  2. Oxygen Extraction: regolith processing/oxygen generation, O_2 cleaning, reactant regeneration
  3. Cryogenic: Stationary O_2/H_2 liquefaction and storage, transfer, mobile O_2/H_2 tankers
     - Stationary O_2/H_2 unit either lander descent tanks or dedicated/deployed
  4. ISRU Power: ~55 KWe or 20 KWe/35 KWt
     - Solar array & regenerative fuel cell for electrical (nuclear reactor optional)
     - Solar concentrator for thermal energy (ex. Carbothermal reduction)
- **Nominal Mission**
  - 10,000 kg oxygen / yr (225 days continuous); 3 modules of 3,500 kg each
  - Highland regolith (iron poor)
  - Regolith delivery/removal traverse paths 100 m to 1000 m
    - Multiple traverses per day
    - Roads/surface stabilization may be required



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

NOTE: Both solar arrays create a width of 15.34 m


ISRU O_2 Plant Power System

Landing/Ascent Pad Area

1000 meters

Mobile Tanker

Waste Dump site

100 m

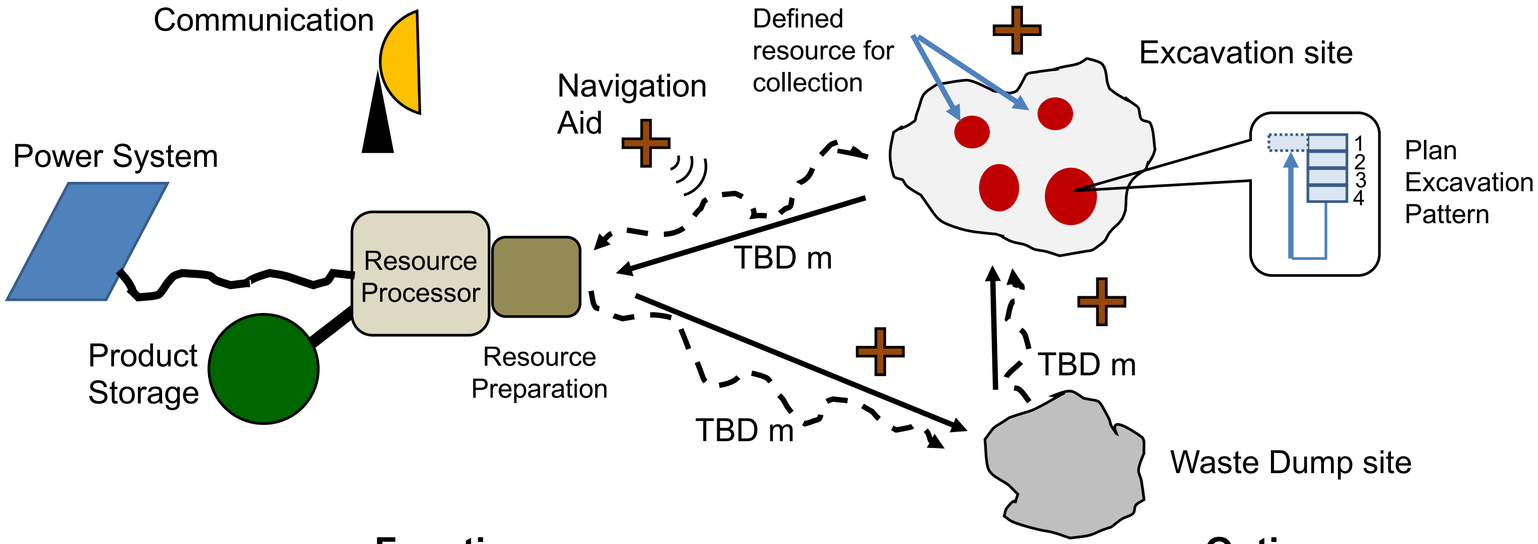
Excavator

Resource Excavation site

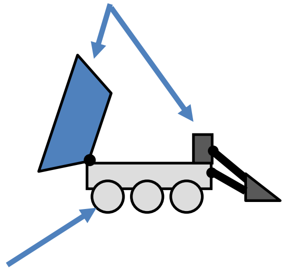
Deliver Propellant to Lander

Deliver/Take Away Regolith

ISRU Concepts of Operation – Oxygen/Metal Extraction



Implements
- Removable / Exchangeable
- Common structure, data, electrical interface



High Traction Mobility Platform
- Removable/ Exchangeable Parts
- Common motors/parts with Implements

⇢ = Unprepared path
→ = Prepared path
TBD = 100 to 1000 m

- **Central Control** – Commands multiple assets
- **Smart Platforms** – Each is aware of what the others are doing

Functions	Options
Traverse back and forth from desired endpoints: plant, resource zone, dump zone	• Smart control and sensors on rover: it selects its own path and avoids obstacles • Path selected on Earth, rover follows path: internal nav or external beacons
Rover selects location for drilling/excavation	• Patterns / locations selected on Earth • Location determined as rover arrives based on past knowledge and site survey • Rover goes to location: internal nav, external beacons, and/or imaging/LIDAR
Device interacts with soil/regolith	• Operate extraction device depending on material: drill, auger, downhole scoop, bucket-wheel/drum, ripper, etc • Pre-planned motions, force-feedback autonomous, human controlled.
Rover interacts with ISRU Plant	• Locates and delivers soil/regolith for processing; Locates and receives spent regolith • Locates dirty water transfer connection for On-rover soil processing • Locates and connects to charging port for battery or fuel cell resupply
ISRU Plant processes regolith	• Pre-established operating conditions and timelines • Regolith pre/post evaluation for process efficiency evaluation and adjustment

Strategy For ISRU Insertion into Human Exploration

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

- **Perform ground develop of hardware and systems until flight decision**
  - 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** through multiple means, including public-private partnerships, to lay the foundation for long-term lunar economic development

- **Utilize CLPS precursor missions to**:
  - 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
    - Fly technologies that are most dependent on interacting with the regolith
    - Fly the components that need to interact with large amounts of real lunar soil in a vacuum environment to prove out longevity/robustness
  - 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 ‘Catch-22’ cycle of past ISRU development priority and architecture insertion issues by developing and flying ISRU demonstrations and capabilities to the Pilot Plant phase.

ISRU Development and Implementation Challenges

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, 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 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?

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

NASA Mission Directorate Roles in ISRU

Space Technology (STMD)

➢ Primary Developer for ISRU
  - Technology development through all TRLs (NIAC, SBIR, ESI/ECF, GCD, Tipping Point, TDM, CIF)
  - Lunar Surface Innovation Initiative: New for FY20 - ISRU development & CLPS payloads
- ISRU Flight Activities
  - MOXIE
  - PRIME-1
  - Future CLPS

Human Exploration & Operation (HEOMD)

➢ Primary Customer for ISRU
  - Mission requirements, needs, and timelines
  - Mission Element Leads: Gateway, Human Lander System (HLS), Lunar Surface Capability (LSC)
  - Full scale ISRU systems & mission implementation
- ISRU Full Scale Implementation
- ISRU Flight Activities
  - MOXIE
  - Lunar Cubesats
  - ShadowCam

Science (SMD)

➢ Primary Supplier of Resource and Landing Site Information
- ISRU Technology and System Development
  - Relevant technologies from missions, ROSES and internal development
- ISRU Flight Activities
  - Hosting MOXIE on Mars 2020 Rover
  - CLPS Resource Assessment Instruments
  - Dev. And Advancement of Lunar Instruments
  - VIPER
  - Lunar Trailblazer SIMPLEx-2

STMD Technology Pipeline

SBIR/STTR

Early Stage Innovation

- NASA Innovative Advanced Concepts
- Space Tech Research Grants
- Center Innovation Fund/Early Career Initiative

Technology Maturation

- Game Changing Development

Partnerships & Technology Transfer

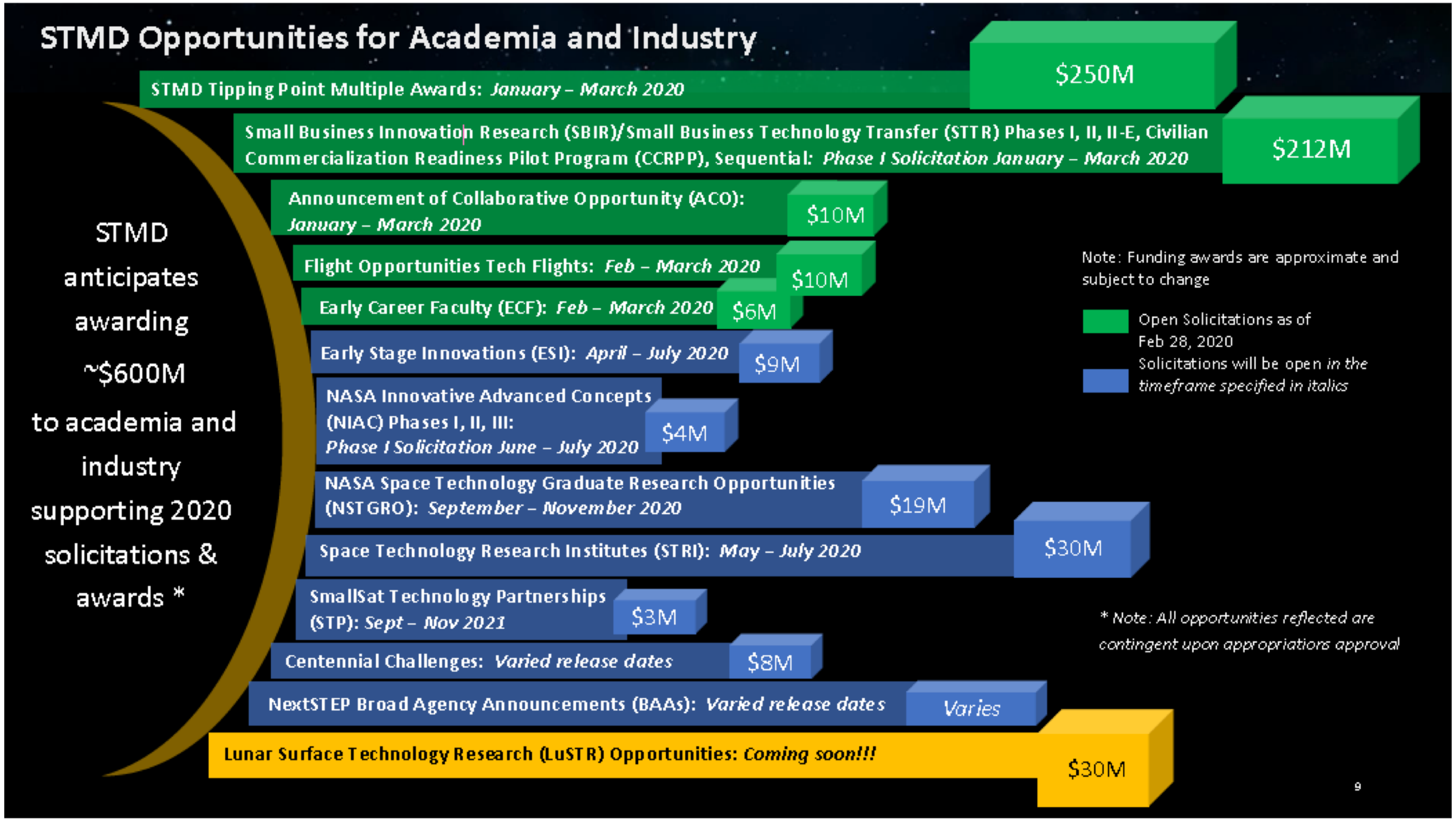
- Technology Transfer
- Prizes and Challenges
- iTech
- Announcement of Collaboration Opportunity
- Tipping Point

Technology Demonstrations

- Technology Demonstration Missions
- Small Spacecraft Technology
- Flight Opportunities

TECHNOLOGY PIPELINE

ISRU Technology/Capability Needs Are Coordinated Across Multiple Solicitations depending on TRL and Developer Target



STMD Opportunities for Academia and Industry

STMD anticipates awarding ~$600M to academia and industry supporting 2020 solicitations & awards *

STMD Tipping Point Multiple Awards: *January – March 2020*	$250M
Small Business Innovation Research (SBIR)/Small Business Technology Transfer (STTR) Phases I, II, II-E, Civilian Commercialization Readiness Pilot Program (CCRPP), Sequential: *Phase I Solicitation January – March 2020*	$212M
Announcement of Collaborative Opportunity (ACO): *January – March 2020*	$10M
Flight Opportunities Tech Flights: *Feb – March 2020*	$10M
Early Career Faculty (ECF): *Feb – March 2020*	$6M
Early Stage Innovations (ESI): *April – July 2020*	$9M
NASA Innovative Advanced Concepts (NIAC) Phases I, II, III: *Phase I Solicitation June – July 2020*	$4M
NASA Space Technology Graduate Research Opportunities (NSTGRO): *September – November 2020*	$19M
Space Technology Research Institutes (STRI): *May – July 2020*	$30M
SmallSat Technology Partnerships (STP): *Sept – Nov 2021*	$3M
Centennial Challenges: *Varied release dates*	$8M
NextSTEP Broad Agency Announcements (BAAs): *Varied release dates*	*Varies*
Lunar Surface Technology Research (LuSTR) Opportunities: *Coming soon!!!*	$30M

Note: Funding awards are approximate and subject to change

🟩 Open Solicitations as of Feb 28, 2020

🟦 Solicitations will be open *in the timeframe specified in italics*

** Note: All opportunities reflected are contingent upon appropriations approval*

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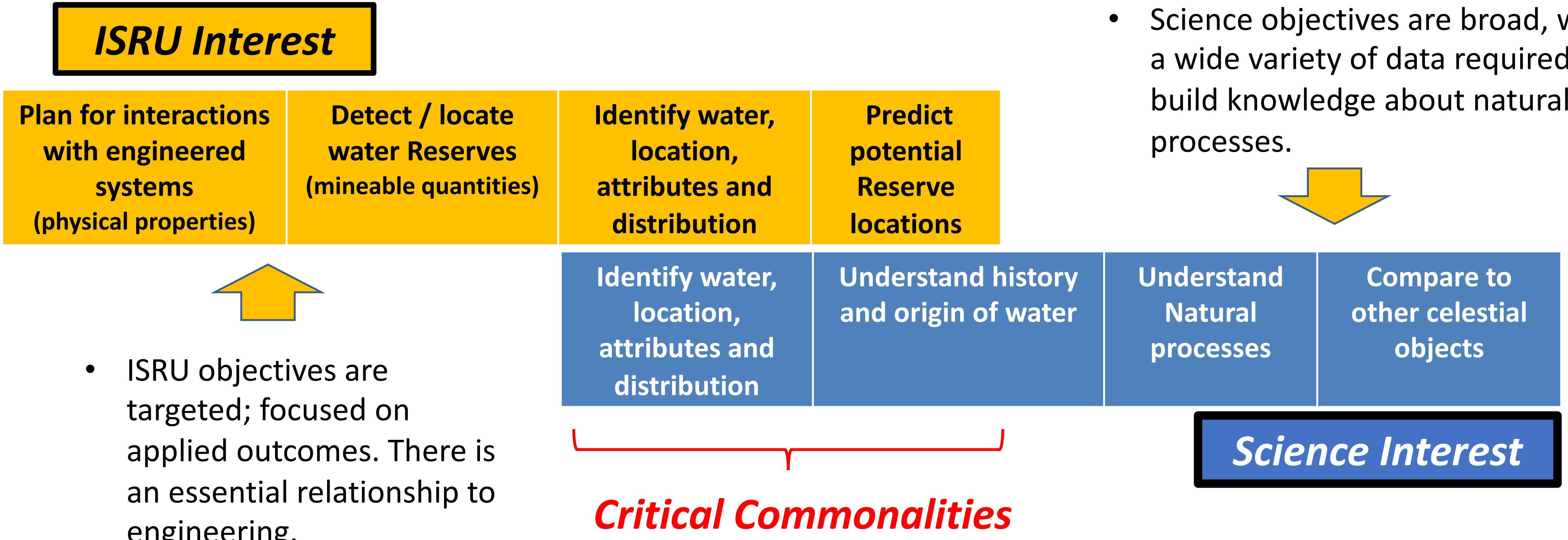
- ➢ NASA internal solicitation/competitions through PPBE and CIF activities
- ➢ Resource Assessment instruments also covered in multiple SMD solicitations: NPLP, LSITP, DALI, PRISM

Backup

ISRU and Science: Commonalities and Differences on Polar Resource Assessment

While Science and ISRU have common measurement needs that will support one another; distinct data sets are required for each.



ISRU Interest

Plan for interactions with engineered systems (physical properties)	Detect / locate water Reserves (mineable quantities)	Identify water, location, attributes and distribution	Predict potential Reserve locations

- ISRU objectives are targeted; focused on applied outcomes. There is an essential relationship to engineering.

- Science objectives are broad, with a wide variety of data required to build knowledge about natural processes.

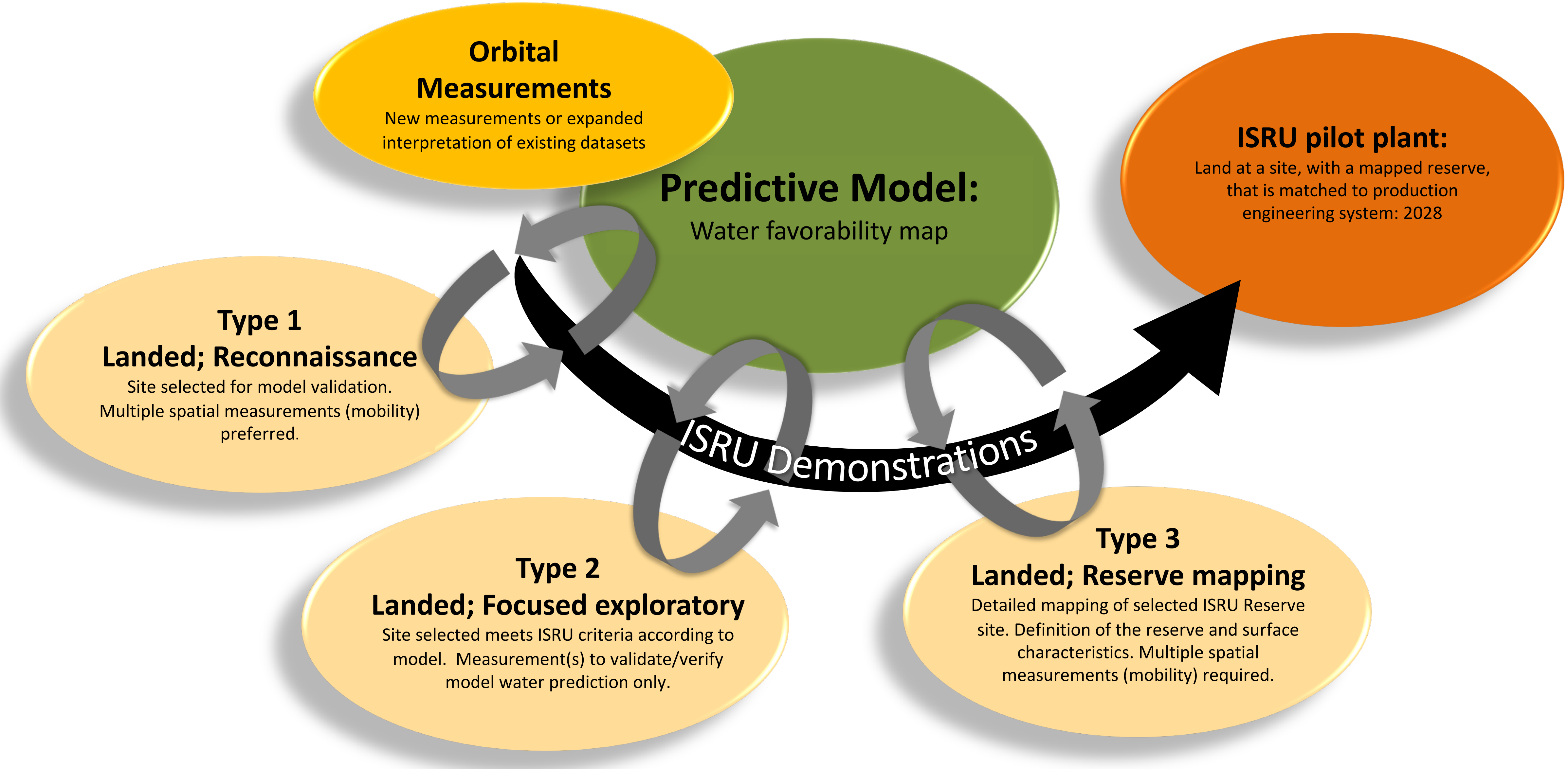
Identify water, location, attributes and distribution	Understand history and origin of water	Understand Natural processes	Compare to other celestial objects

Science Interest

Critical Commonalities

Resource Assessment:

Measurement Strategy Leading to Final Site Selection and ISRU Pilot Plant



Orbital Measurements

New measurements or expanded interpretation of existing datasets

Predictive Model:

Water favorability map

ISRU pilot plant:

Land at a site, with a mapped reserve, that is matched to production engineering system: 2028

Type 1

Landed; Reconnaissance

Site selected for model validation. Multiple spatial measurements (mobility) preferred.

ISRU Demonstrations

Type 2

Landed; Focused exploratory

Site selected meets ISRU criteria according to model. Measurement(s) to validate/verify model water prediction only.

Type 3

Landed; Reserve mapping

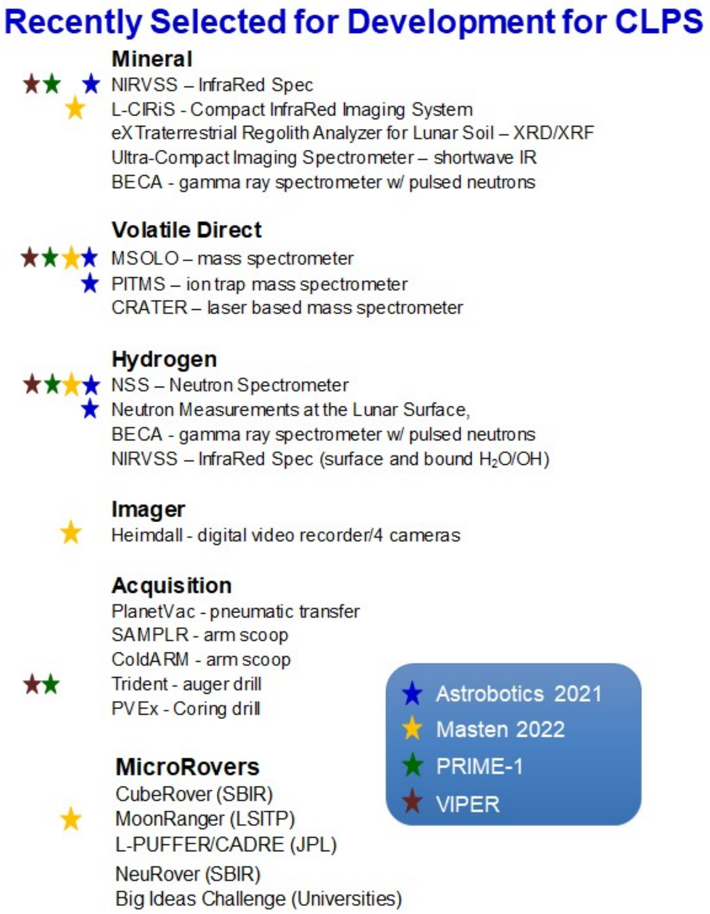
Detailed mapping of selected ISRU Reserve site. Definition of the reserve and surface characteristics. Multiple spatial measurements (mobility) required.

SMD Lunar Discovery and Exploration Program

- **Instrument Development and Delivery**
  - Maturation of instrument concepts (DALI)
    - 10 teams funded to mature CLPS instruments:
  - Instruments for First CLPS Missions
    - NASA Provided Lunar Payloads (NPLP) – 13 instruments selected
    - Lunar Surface Instruments, technology & exploration (LSITP) – 12 instruments
  - Instruments for next CLPS Missions
    - Payloads and Research Investigations on the Surface of the Moon (PRISM)

- **Ground Development and Science**
  - Long duration rover investments
  - Apollo Next Generation Sample Analysis (ANGSA)

- **Current and Future Flight Missions**
  - Lunar Reconnaissance Orbiter (LRO) Mission Operations
  - Lunar SmallSats
    - Cubesats/SmallSats delivered by CLPS
    - SIMPLEX: Lunar Trailblazer
  - Commercial Lunar Payload Services
    - CPLS 1 & CPLS 2 in 2021: Astrobotics & Intuitive Machines
    - CLPS 3 in 2022: Masten
    - Volatiles Investigating Polar Exploration Rover (VIPER) in 2023
    - Follow on missions approximately every 24 months



Recently Selected for Development for CLPS

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

Hydrogen
★★★★ NSS – Neutron Spectrometer
★ Neutron Measurements at the Lunar Surface,
BECA - gamma ray spectrometer w/ pulsed neutrons
NIRVSS – InfraRed Spec (surface and bound H_2O/OH)

Imager
★ Heimdall - digital video recorder/4 cameras

Acquisition
PlanetVac - pneumatic transfer
SAMPLR - arm scoop
ColdARM - arm scoop
★★ Trident - auger drill
PVEx - Coring drill

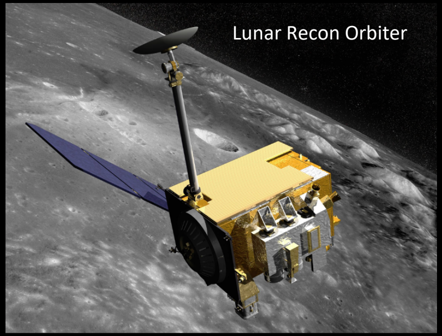
MicroRovers
CubeRover (SBIR)
★ MoonRanger (LSITP)
L-PUFFER/CADRE (JPL)
NeuRover (SBIR)
Big Ideas Challenge (Universities)

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

Current NASA ISRU-Related Instruments & Orbital Missions

Lunar Reconnaissance Orbiter (LRO) – 2009 to Today

- Lyman-Alpha Mapping Project (LAMP) – UV;
- Lunar Exploration Neutron Detector (LEND) - Neutron;
- Diviner Lunar Radiometer Experiment (DLRE) – IR;
- Cosmic Ray Telescope for the Effects of Radiation (CRaTER) – Radiation;
- Lunar Orbiter Laser Altimeter (LOLA)
- Lunar Reconnaissance Orbiter Camera (LROC) – Sun/Imaging;
- Mini-RF Radar

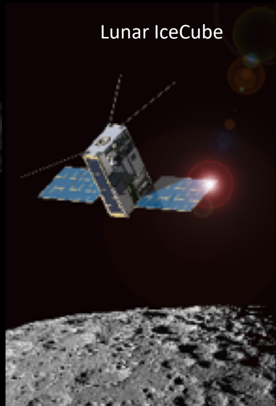


Korea Pathfinder Lunar Orbiter (KPLO) – 2022

- ShadowCam Map reflectance within permanently shadowed craters

Science/Prospecting Cubesats (SLS Artemis-1 2021)

- 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



Lunar Trailblazer (SIMPLEx) – TBD

- Miniaturized imaging spectrometer and multispectral thermal imager

Location to Reduce/Eliminate ISRU Challenges/Risks
- Ground vs Flight

- Most challenges and risks to ISRU development and incorporation can be eliminated through design and testing under Earth analog or environmental chamber testing at the component, subsystem, and system level
  - **Adequate simulants are critical for valid Earth based testing**
- ① Critical challenges/risks associated with fully understanding the extraterrestrial resource (form, concentrations, contaminants, etc.) and ISRU system operation under actual environmental conditions for extended periods of time can only be performed on the extraterrestrial surface
- ② Product quality based on actual *in situ* resource used should be validated at the destination
- ISRU precursors/demonstrations are extremely beneficial for validation of Earth-based testing and analysis

ISRU Challenge/Risk		Earth	Orbit	Surface	
R1	What resources exist at the site that can be used?	S	S	**P**	①
R2	What are the uncertainties associated with these resources?	S	S	**P**	
R3	How to Address planetary protection requirements?	**P**		V	
T1	Is it technically feasibile to collect, extract, & process resources?	**P**		V	
T2	What is needed to achieve long duration, autonomous operation?	**P**		V	
O1	What is needed to achieve high reliability and/or maintenance?	**P**		V	
O2	What is needed to operate in extreme environments?	S/V	$\mathbf{P}_{\mathbf{NEA}}$	**P**	①
O3	What is needed to operate in low/micro gravity?	S	$\mathbf{P}_{\mathbf{NEA}}$	**P**	
O4	How to survive and operate after long duration dormancy ?	P		S	
I1	How can other systems be designed to use ISRU products?	**P**		V/**P**	②
I2	How to optimize designs at the architecture level with ISRU?	**P**		V	
I3	How to manage ISRU interfaces/interactions with other systems?	**P**		V	

P = Primary Location; S = Support Location; V = Validation Location