NASA Lunar ISRU Strategy

Presented at the
What Next for Space Resource Utilization? Workshop
Luxembourg

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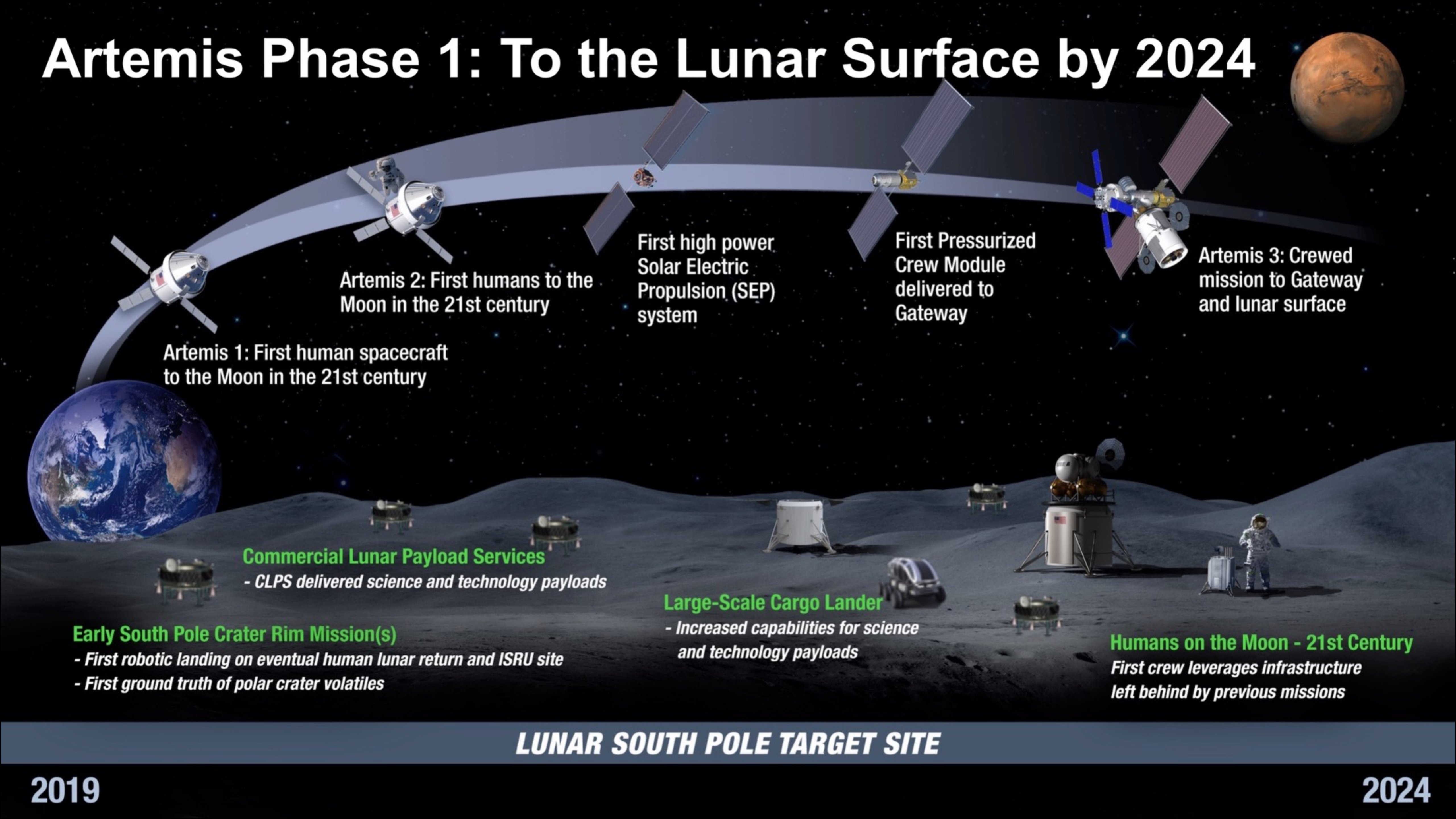
Gerald Sanders/NASA ISRU SCLT


Artemis Phase 1: To the Lunar Surface by 2024
Artemis 1: First human spacecraft to the Moon in the 21st century
Artemis 2: First humans to the Moon in the 21st century
First high power Solar Electric Propulsion (SEP) system
First Pressurized Crew Module delivered to Gateway
Artemis 3: Crewed mission to Gateway and lunar surface
Commercial Lunar Payload Services
- CLPS delivered science and technology payloads
Early South Pole Crater Rim Mission(s)
- First robotic landing on eventual human lunar return and ISRU site
- First ground truth of polar crater volatiles
Large-Scale Cargo Lander
- Increased capabilities for science and technology payloads
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE TARGET SITE
2019
2024

Lunar Science by 2024

Polar Landers and Rovers

- First direct measurement of polar volatiles, improving understanding of lateral and vertical distribution, physical state, and chemical composition
- Provide geology of the South-Pole Aitken basin, largest impact in the solar system

Non-Polar Landers and Rovers

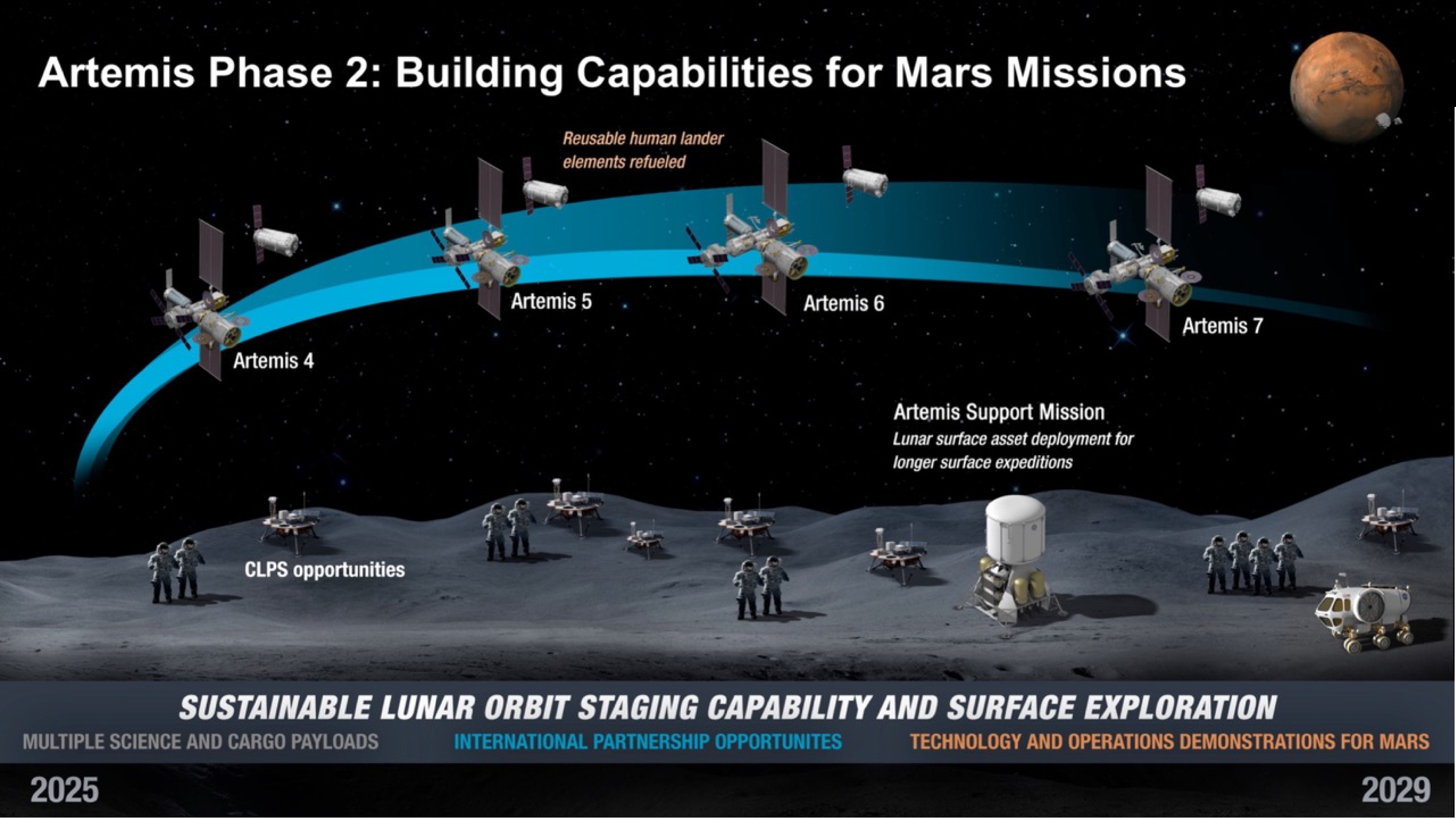
- Explore scientifically valuable terrains not investigated by Apollo, including landing at a lunar swirl and making first surface magnetic measurement
- Using PI-led instruments to generate Discovery-class science, like establishing a geophysical network and visiting a lunar volcanic region to understand volcanic evolution

Orbital Data

- Deploy multiple CubeSats with Artemis 1
- Potential to acquire new scientifically valuable datasets through CubeSats delivered by CLPS providers or comm/relay spacecraft
- Global mineral mapping, including resource identification, global elemental maps, and improved volatile mapping

In-Situ Resource Initial Research

- Answering questions on composition and ability
  to use lunar ice for sustainment and fuel


Artemis Phase 2: Building Capabilities for Mars Missions
Reusable human lander elements refueled
Artemis 4
Artemis 5
Artemis 6
Artemis 7
Artemis Support Mission
Lunar surface asset deployment for longer surface expeditions
CLPS opportunities
SUSTAINABLE LUNAR ORBIT STAGING CAPABILITY AND SURFACE EXPLORATION
MULTIPLE SCIENCE AND CARGO PAYLOADS
INTERNATIONAL PARTNERSHIP OPPORTUNITES
TECHNOLOGY AND OPERATIONS DEMONSTRATIONS FOR MARS
2025
2029

NASA Lunar ISRU Purpose

EXPLORE MOONtoMARS

Lunar ISRU To Sustain and Grow Human Lunar Surface Exploration

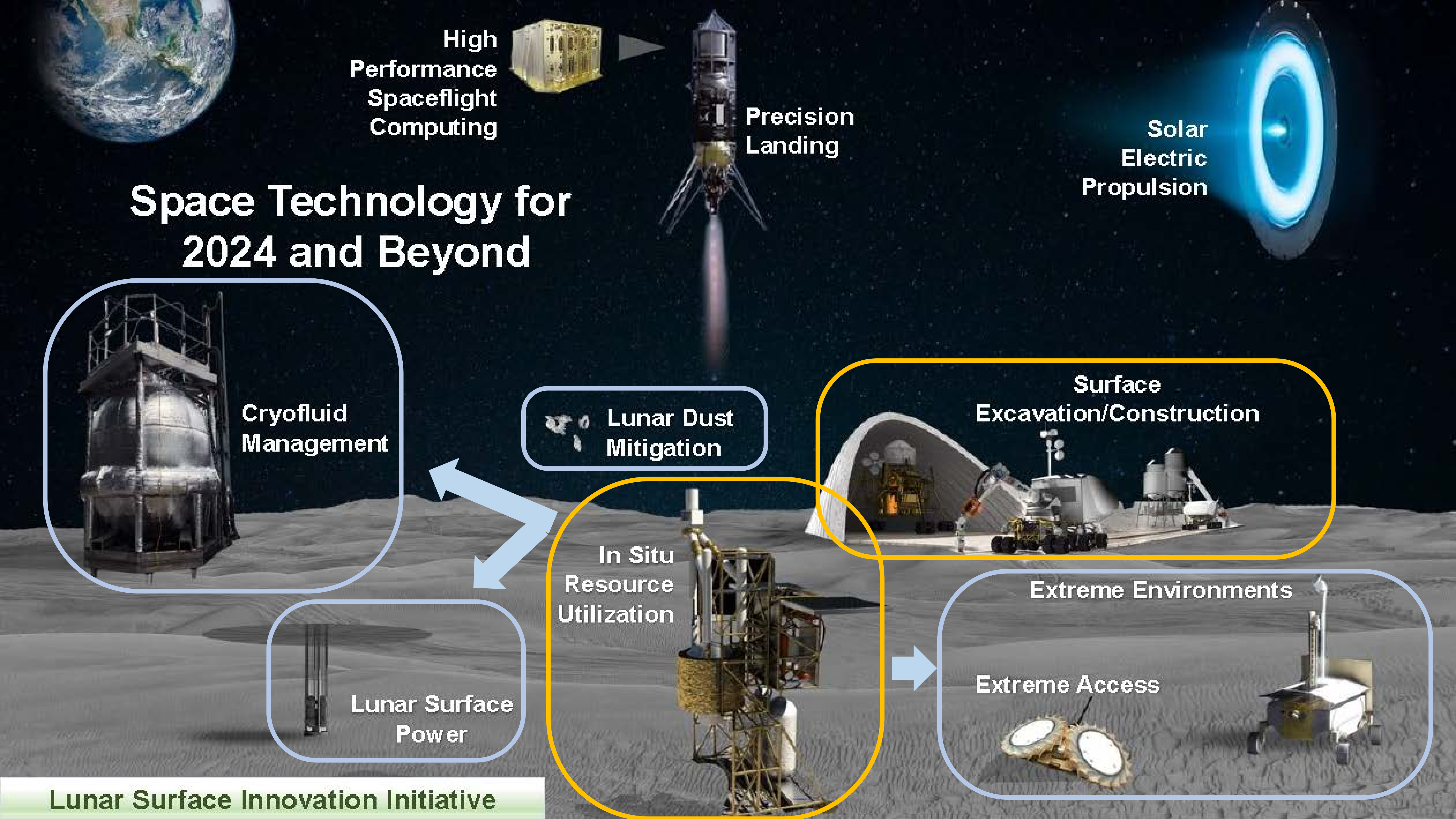
- Lunar Resource Characterization for Science and Prospecting
  - Provide ground-truth on physical, mineral, and volatile characteristics – provide geological context;
  - Test technologies to reduce risk for future extraction/mining
- **Mission Consumable Production (O_2, H_2O, Fuel):**
- Learn to Use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

- Lunar Polar Water/Volatiles is Game Changing/Enabling
- Promote Commercial Operations/Business Opportunities
- Support/promote establishment of reusable/commercial transportation



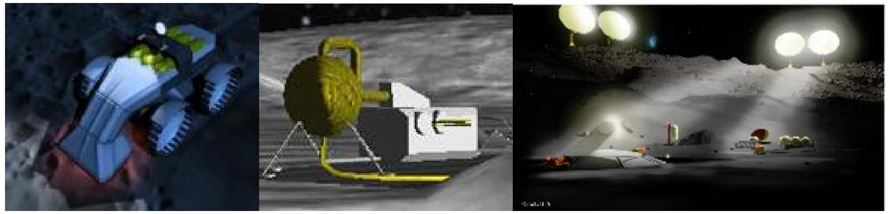
High Performance Spaceflight Computing
Precision Landing
Solar Electric Propulsion
Space Technology for 2024 and Beyond
Cryofluid Management
Lunar Dust Mitigation
Surface Excavation/Construction
In Situ Resource Utilization
Extreme Environments
Extreme Access
Lunar Surface Power
Lunar Surface Innovation Initiative

Lunar Surface ISRU Capabilities

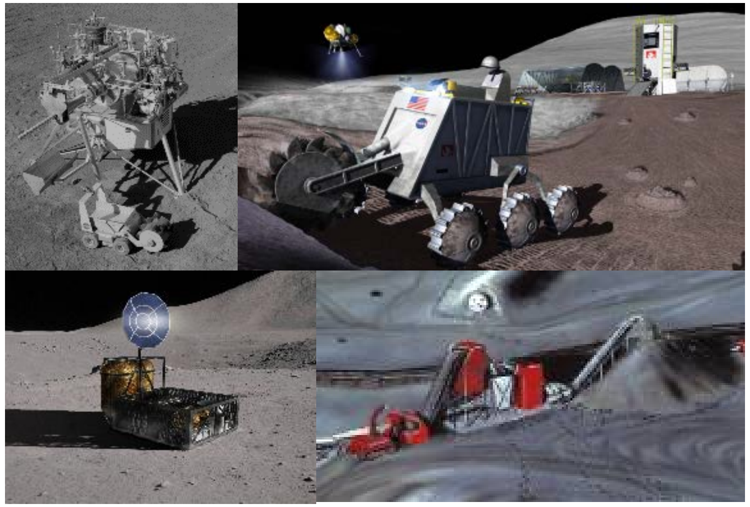
EXPLORE MOON to MARS

Resource Prospecting – Looking for Water

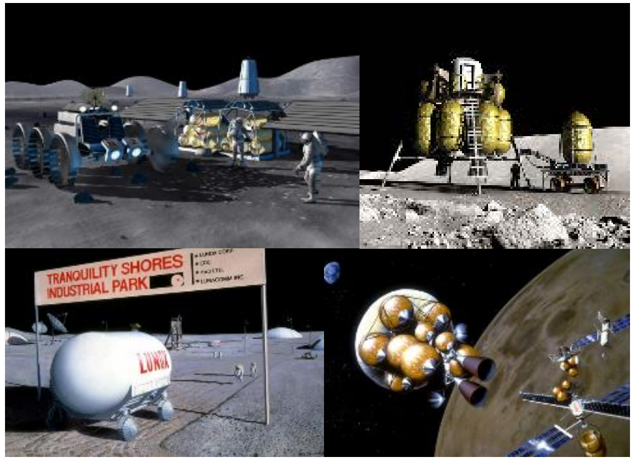
Mining Polar Water & Volatiles



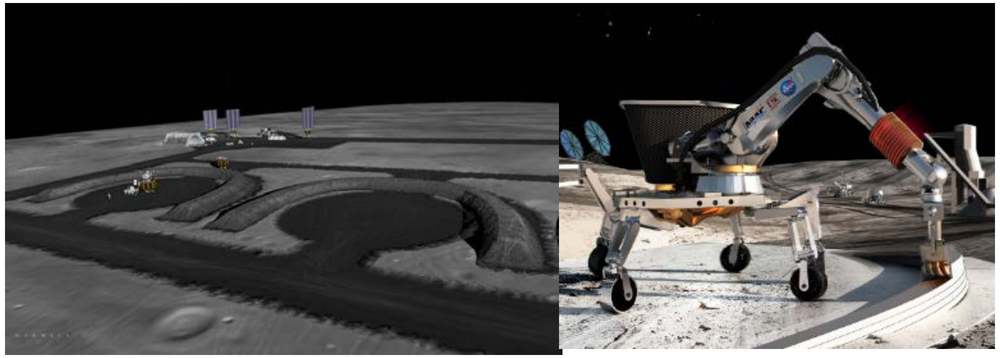
Excavation & Regolith Processing for O_2 & Metal Production



Refueling and Reusing Landers & Rovers

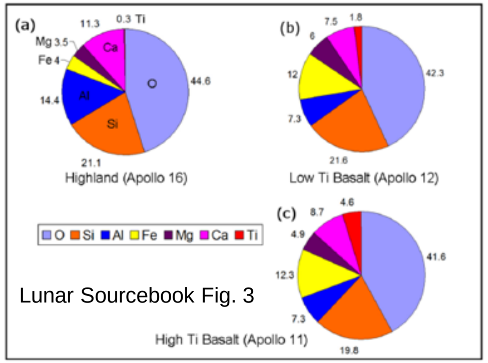


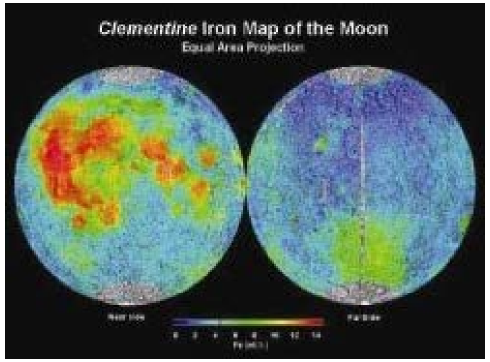
Landing Pads, Berms, Roads, and Structure Construction



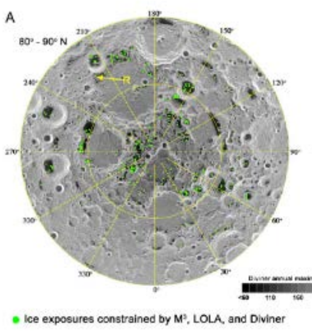
Lunar Resources

Regolith, Solar Wind Volatiles, Polar Water/Volatiles

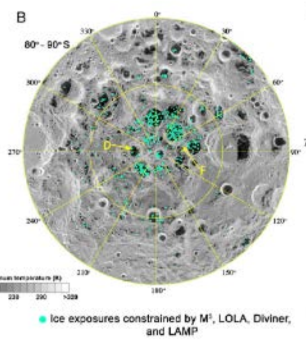




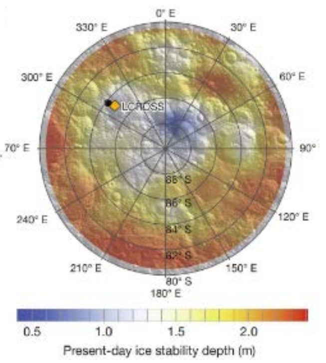
North Pole



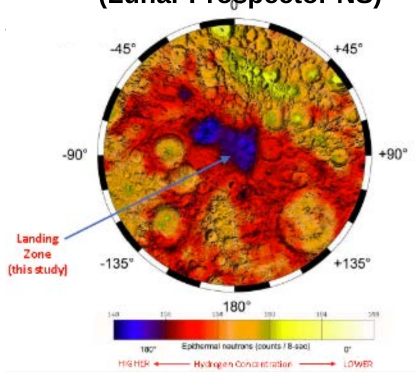
South Pole



Ice Stability Temperatures



Evidence of Hydrogen (Lunar Prospector NS)



Lunar Regolith

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

Fegley and Swindle 1993

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

Polar Water/Volatiles

- LCROSS Impact estimated **5.5 wt%** water in plume
  - Solar wind & cometary volatiles (H_2, NH_3, C_2H_4, CO_2, CH_3OH, CH_4): 0.1 to 1.5 wt%
- **Green and blue dots** show positive results for surface water ice using M^3 and LOLA data for the North pole, and M^3, LOLA, and LAMP data for the South pole.
- Data points also have maximum annual temperatures of <110 K from Diviner data.
- Spectral modeling shows that some ice-bearing pixels may contain **~30 wt % ice** (mixed with dry regolith)
- Ice detections in the south are clustered near the craters Haworth, Shoemaker, Sverdrup, and Shackleton, while those in the north are more isolated.

Lunar ISRU Mission Consumables:
Oxygen from Regolith vs Polar Water

EXPLORE MOON to MARS

- **Oxygen from Regolith**
  - **Lunar regolith is >40% oxygen (O_2) by mass**
  - **Can be incorporated into the architecture from the start with low-moderate risk**
  - **Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth)**
  - Experience from regolith excavation, beneficiation, and transfer applicable to mining Mars hydrated soil/minerals for water and *in situ* manufacturing and constructions

- **Water (and Volatiles) from Polar Regolith**
  - **Form, concentration, and distribution of Water in shadowed regions/craters is not known**
  - **Cannot be incorporated into the architecture from the start with low to moderate risk**
  - **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

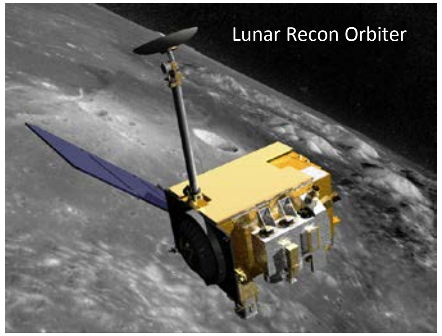
➢ **Current Plan:** Develop and fly demonstrations for both lunar ISRU consumable approaches
  - Develop oxygen extraction to meet near term sustainability objectives
  - Utilize orbital missions and early lunar surface missions to understand and characterize polar environments, regolith, and water resources to address risks and technology needs

Current NASA ISRU-Related Instruments & Orbital Missions

EXPLORE MOON to MARS

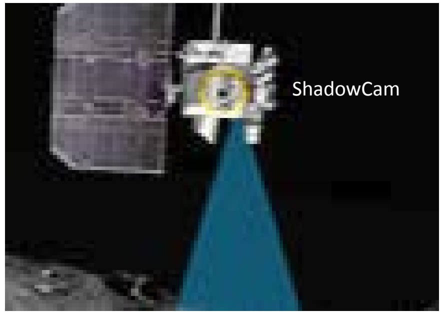
Lunar Reconnaissance Orbiter (LRO) – 2009 to Today

- 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) – 12/2020

- ShadowCam Map reflectance within permanently shadowed craters

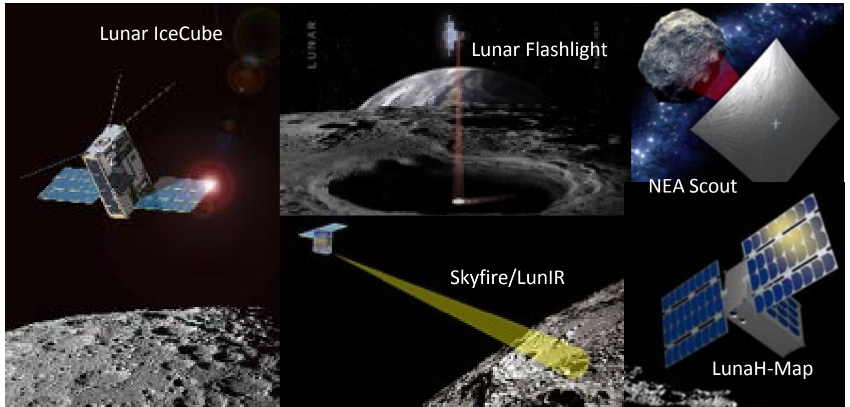


Science/Prospecting Cubesats (SLS Artemis-1 2020)

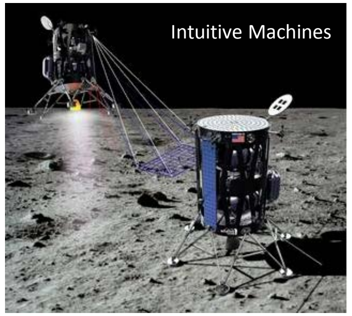
- Lunar Flashlight: Near IR laser and spectrometer to look into shadowed craters for volatiles
- Lunar IceCube: Broadband InfraRed Compact High Resolution Explorer Spectrometer
- LunaH-MAP: Two neutron spectrometers to produce maps of near-surface hydrogen (H)
- Skyfire/LunIR: Spectroscopy and thermography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

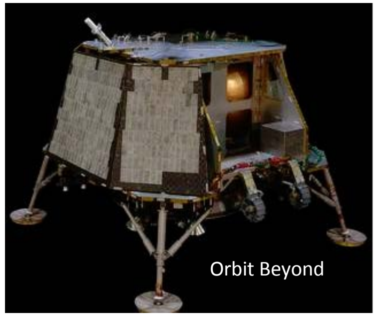
Lunar Trailblazer (SIMPLEx) – TBD

- Miniaturized imaging spectrometer and multispectral thermal imager



Current NASA ISRU-Related Instruments & Surface Missions





Commercial Lunar Payload Services (CLPS)

- Astrobotic: 14 payloads; Lacus Mortis site – 7/21
- Intuitive Machines: 5 payloads; Oceanus Procellarum – 7/21
- Orbit Beyond: 4 payloads; Mare Imbrium – 9/2020

Instruments for CLPS

- 13 NASA internal science & technology payloads
  - Prospecting: NIRVSS – InfraRed Spec, NSS – Neutron Spec, Neutron Measurements at the Lunar Surface, PITMS – ion trap mass spectrometer, MSOLO – mass spectrometer
- 12 external science & technology payloads:
  - Regolith collection: PlanetVac and Sample Acquisition, Morphology Filtering, and Probing of Lunar Regolith (SAMPLR)
  - Lunar Compact InfraRed Imaging System (L-CIRiS)

Dev. And Advancement of Lunar Instruments (DALI) – TBD

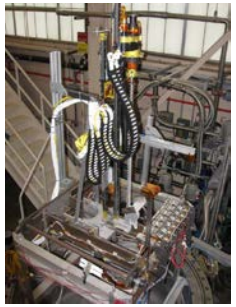
- 10 teams funded to mature CLPS instruments:
  - Beneficial for ISRU prospecting: Submillimeter Solar Observation Lunar Volatiles Experiment (SSOLVE); Characterization of Regolith and Trace Economic Resources (CRATER)- laser MS; Bulk Elemental Composition Analyzer (BECA) – Pulsed neutrons; eXTraterrestrial Regolith Analyzer for Lunar Soil – XRD/XRF; Ultra-Compact Imaging Spectrometer – shortwave IR; Electrostatic Dust Analyzer (EDA)

Volatiles Investigation Polar Exploration Rover

- Prospecting rover to fly to south polar region on late 2022

Polar Resource Ice-Mining Experiment-1 (PRIME-1) – TBD

- FY19 Drill down-select with mass spectrometer

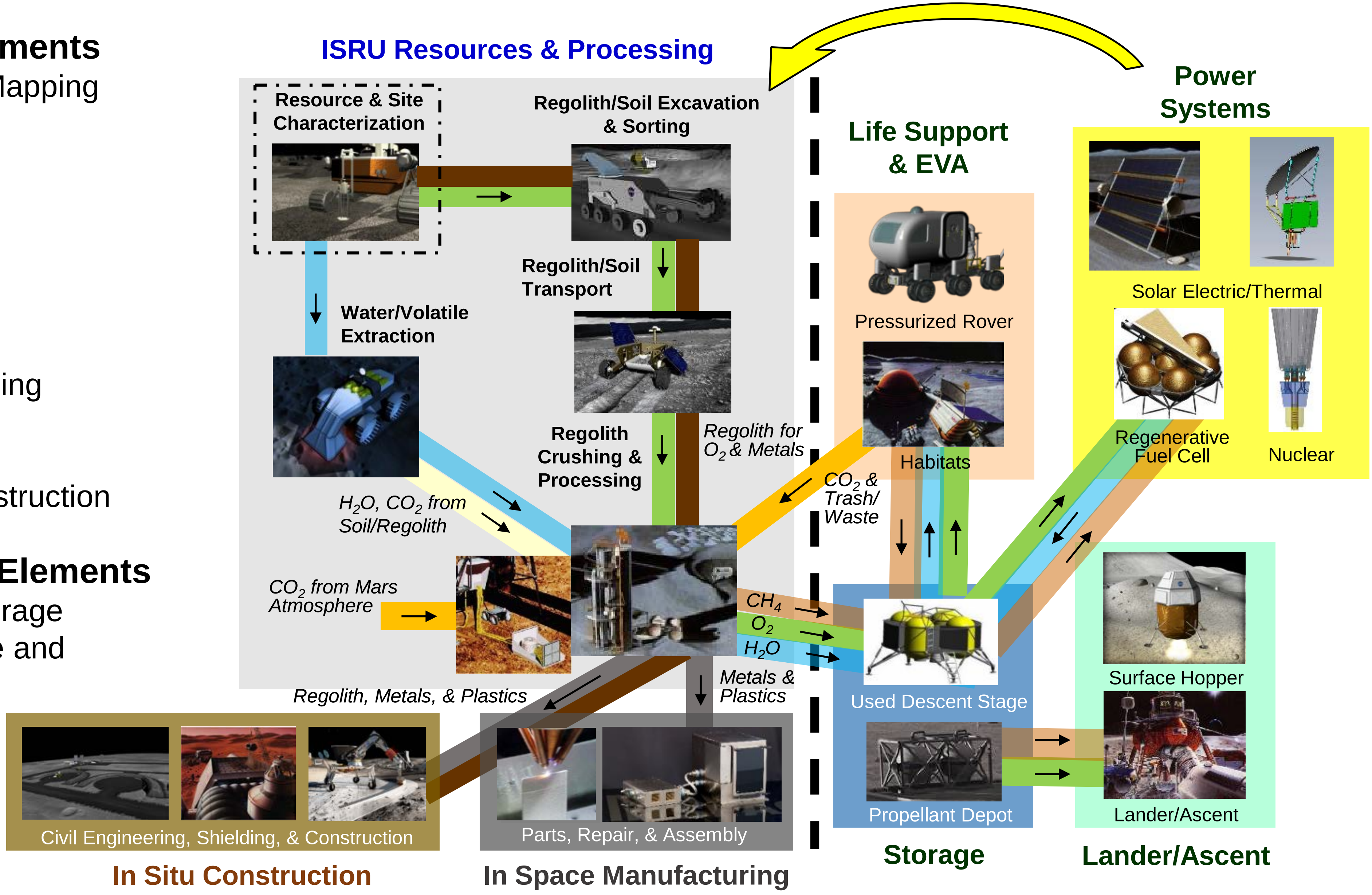


Backup/Optional

Integration of ISRU with Exploration Elements
(Mission Consumables)

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

Support Functions & Elements
- Power Generation & Storage
- O_2, H_2, and CH_4 Storage and Transfer



ISRU Capability & Gap Assessment
Lunar Polar Water/Volatile Mining

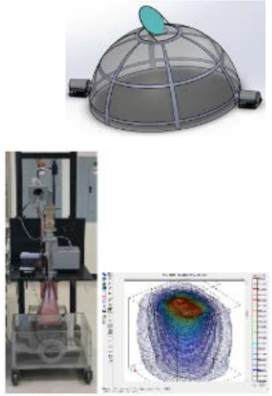
- <u>Current State of Development</u>: Proof of Concept Development
  - At least 8 concepts are currently being explored including:
    - Excavation w/ Auger dryer
    - Heated coring auger
    - Microwave heating
    - Heated Dome
  - 3 Architectural Approaches:
    - Excavate in PSR and remove to sunlit region for processing
    - Excavate/process in PSR and move water to sunlit region for processing
      - > On multiple mobile platforms
      - > Multiple excavators deliver to centralized processor
    - In situ (underground) process and move water to sunlit region
- <u>Gap</u>
  - ***Continue development of multiple options to advance to TRL 6 until polar data is available***
  - ***Long-duration testing (100's of days)***
  - ***Increase autonomy and maintainability***
  - ***Lunar environmental testing***

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

Centralized Processor: Auger Dryer

Mobile Processor: MISWE and PVEx

In Situ Processor: Microwave & Dome



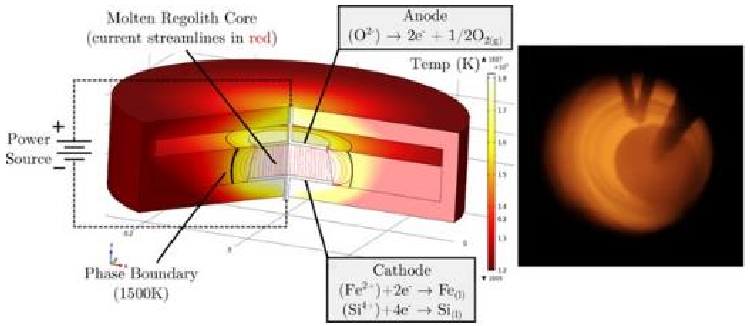
Polar H_2O		
Auger/ Reactor	PVEx	Subsurface Heating/ Dome
Poor - Orbital Low Resolution - LCROSS Impact		
High (Permanently Shadowed Crater/Regions Near extensive sunlight)		
Low (<150 C)		
Low ?		
Dependant on water concentration & regolith hardness		
4-5	3	1-2

ISRU Capability
Oxygen Extraction from Regolith

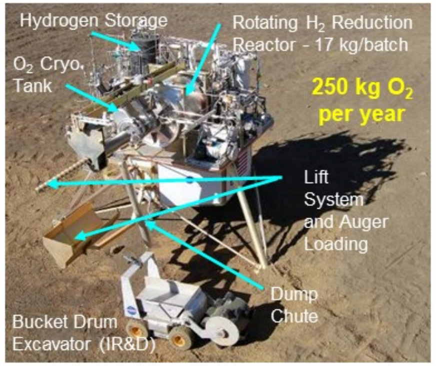
- <u>Current State of Development</u>: Engineering Breadboards – TRL 3 to 5
  - Over 20 processes have been identified to extract oxygen from regolith
    - Components required range from TRL 3 to TRL 9
    - Typically, as processing temps increase, O_2 yield increases, and technical and engineering challenges increase
  - Constellation Program focused on three processes
    1. Hydrogen (H_2) reduction
    2. Carbothermal (CH_4) reduction
    3. Molten regolith electrolysis
  - Two processes (#1 & 2) developed to TRL 4-5 at human mission relevant scale and tested at analog site for days at sub-pilot scale
  - Examining lower TRL concepts as well

	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	2-3	2

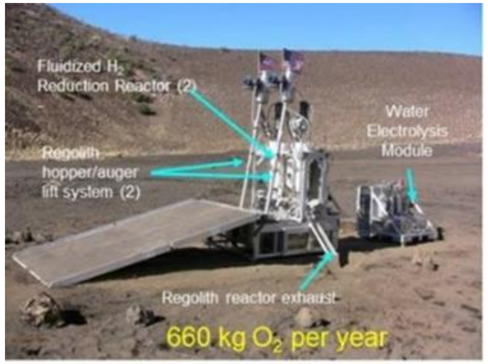
*kg O_2/kg bulk regolith



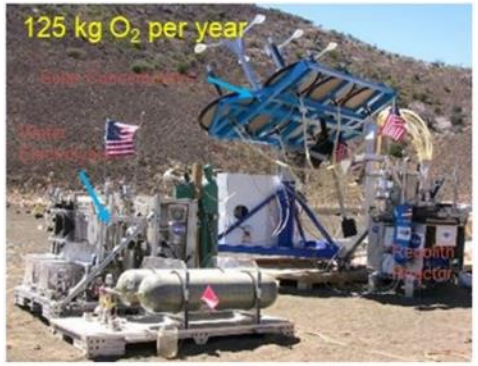
Molten Regolith Reduction



Hydrogen (H_2) Reduction



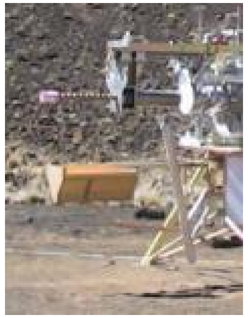
Hydrogen (H_2) Reduction

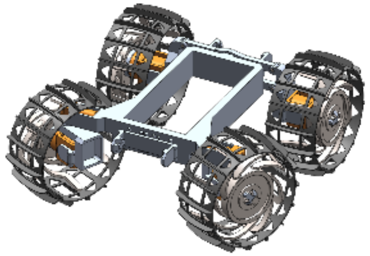


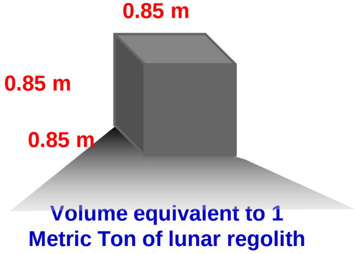
Carbothermal (CH_4) Reduction

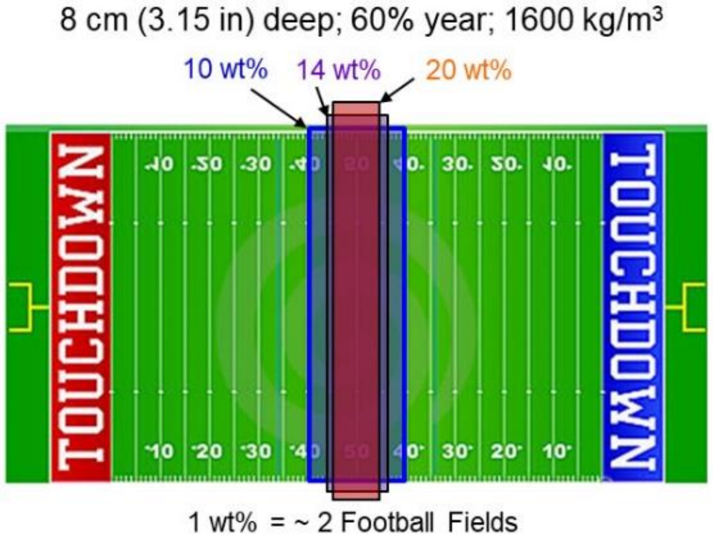
ISRU Capability
Lunar Regolith Excavation, Transfer, and Preparation

- <u>Current State of Development</u>: Eng. Breadboards – TRL 3 to 5
  - Built and tested multiple excavation approaches for granular regolith: scoops, percussive blades, bucket ladders, bucket wheels, bucket drums (NASA, SBIRs, Challenges)
  - Built and tested auger and ripper for hard materials (SBIRs)
  - Built and tested multiple transfer approaches: lift buckets, vertical augers, horizontal augers, pneumatic
  - Examined and lab tested size sorting and mineral separation approaches
  - Built and tested multiple small excavation vehicles (NASA, SBIRs, Challenges)









ISRU Capability
Civil Engineering and *In Situ* Construction

- <u>Current State of Development</u>: Proof of Concept/Eng. Breadboards – TRL 3 to 5

Areas Clearing/Berm Building
- Moses Lake, 2007

Landing Pad Construction: NASA, PISCES, Honeybee Robotics

Grading & Leveling Blade

Compactor Roller

Paver Deployment

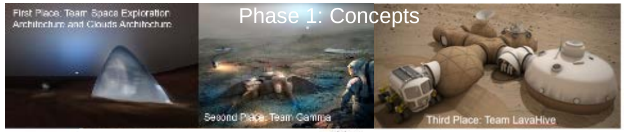
Completed Landing Pad

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

Landing Pad Construction:
CSA, Neptec, ODG, NORCAT

Autonomous area clearing, leveling, and berm building

NASA Centennial Challenge:
3D Printed Habitat ($2.5 Million Prize)



3D Printed Habitat CHALLENGE

Phase 2: Structural Member Competition

Phase 2: 1.5 m Printed Dome

Phase 3: Structure Fabrication – April 2019

Synthetic Biology
- CO_2 Based Manufacturing
- BioMaterials
- Center for Utilization of Biological Engineering in Space (CUBES)

Sintering
- Solar Concentrator
- Radiative heating

Additive Construction with Mobile Emplacement (ACME)
- 2D and 3D printing on a large (structure) scale using in-situ resources as construction materials

Automated Construction for Expeditionary Structures (ACES) - NASA with U.S. Army Corps of Engineers
- 3D print large structures to support deployment in remote areas

Lunar Mobility Strategy

- Primary drivers include science and human exploration objectives and soonest landing; target is late 2022 in the South Pole region
- Primary objectives:
    - ➢ Ground truth of volatiles (horizontal and vertical distribution, composition, and form)
    - ➢ Long duration operation (months)

- Parallel Rover Development Paths
    - NASA in-house development (VIPER)
    - Study task order to existing CLPS providers
    - RFI to industry to determine potential commercial sources and availability
    - Investigate international contribution (e.g., ESA, CSA)

Lunar Discovery and Exploration Program (LDEP)

- **Commercial Lunar Payload Services (CLPS)**
  - Two deliveries per year
  - Drive to enable community-driven science
- **Instrument Development and Delivery**
  - Instruments for CLPS
  - Maturation of instrument concepts (DALI)
- **VIPER Polar Rover**
  - NASA-built rover to the lunar surface in late CY2022
    - Delivery by CLPS provider via on-ramp for enhanced capability
- **Follow on missions (commercial rovers) approximately every 24 months**
- **Long Duration Rover Investments**
- **Lunar Reconnaissance Orbiter Mission Operations**
- **Lunar SmallSats**
  - SIMPLEX
  - CubeSats/SmallSats delivered into lunar orbit by CLPS
- **Apollo Next Generation Sample Analysis (ANGSA)**

ISRU Development and Implementation Challenges Must Be Addressed

EXPLORE MOONtoMARS

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?

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