Current NASA *In Situ* Resource Utilization (ISRU) Strategic Vision

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American Leadership in Space Exploration

EARTH ORBIT → LUNAR ORBIT → LUNAR SURFACE → MARS & BEYOND

EARTH ORBIT

- Grow a Robust Commercial Space Industry with a Constant Human Presence
- Expand our International Partnerships through the ISS
- Conduct exploration science and technology demonstrations aboard ISS
- Continue Critical Earth Science Research
- New Jobs through In-Space Manufacturing and Assembly
- Low-Earth orbit launches us to farther destinations

LUNAR ORBIT

- The Next Step for Commercial Space Development
- Conduct Ground-Breaking Decadal Science
- A New Venue to Strengthen International Partnerships
- Stepping Stone and Training Ground for Extending Human Presence into Deep Space
- Sustainable and Affordable Human and Robotic Programs

LUNAR SURFACE

- Seed Investments in Commercial Lunar Landers
- Opportunities to Develop Technologies for Long-Term Survival
- Explore and Exploit Space Resources
- Create a Foothold on a New Frontier

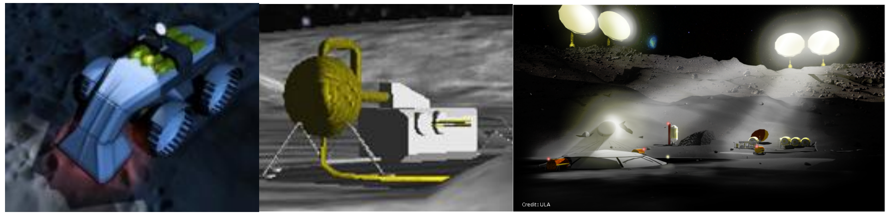
MARS & BEYOND

- America's Next Giant Leap – Reaching New Worlds
- Push the Boundaries of Human Knowledge
- Answer the Question of 'Are we Alone?'
- Unlock the mysteries of the universe

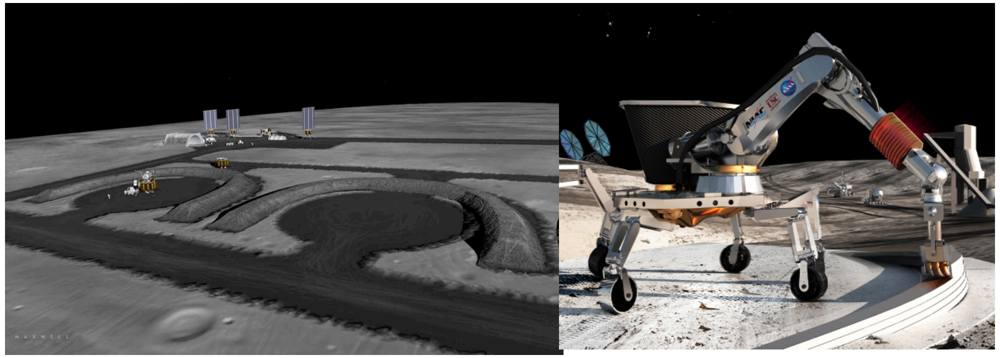
Lunar Surface ISRU Capabilities

Resource Prospecting – Looking for Water

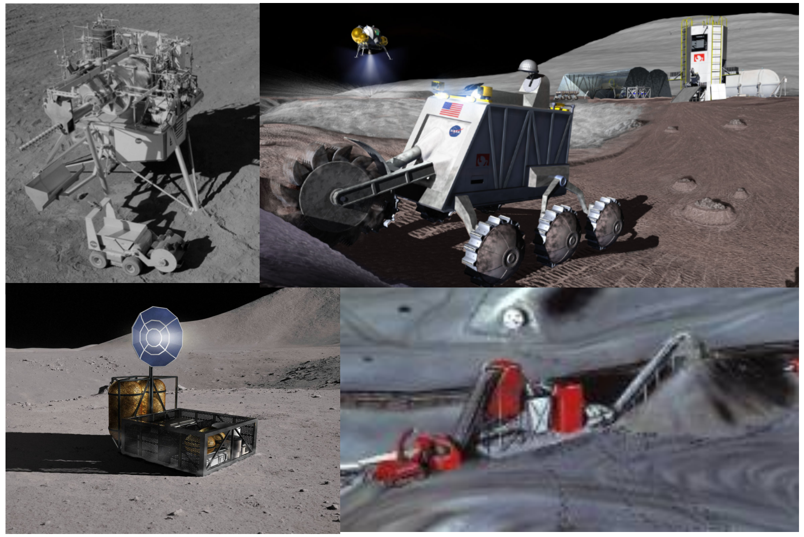
Mining Polar Water & Volatiles



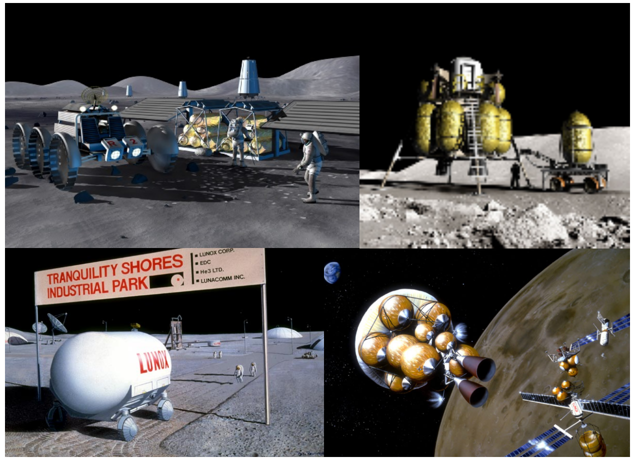
Landing Pads, Berms, Roads, and Structure Construction

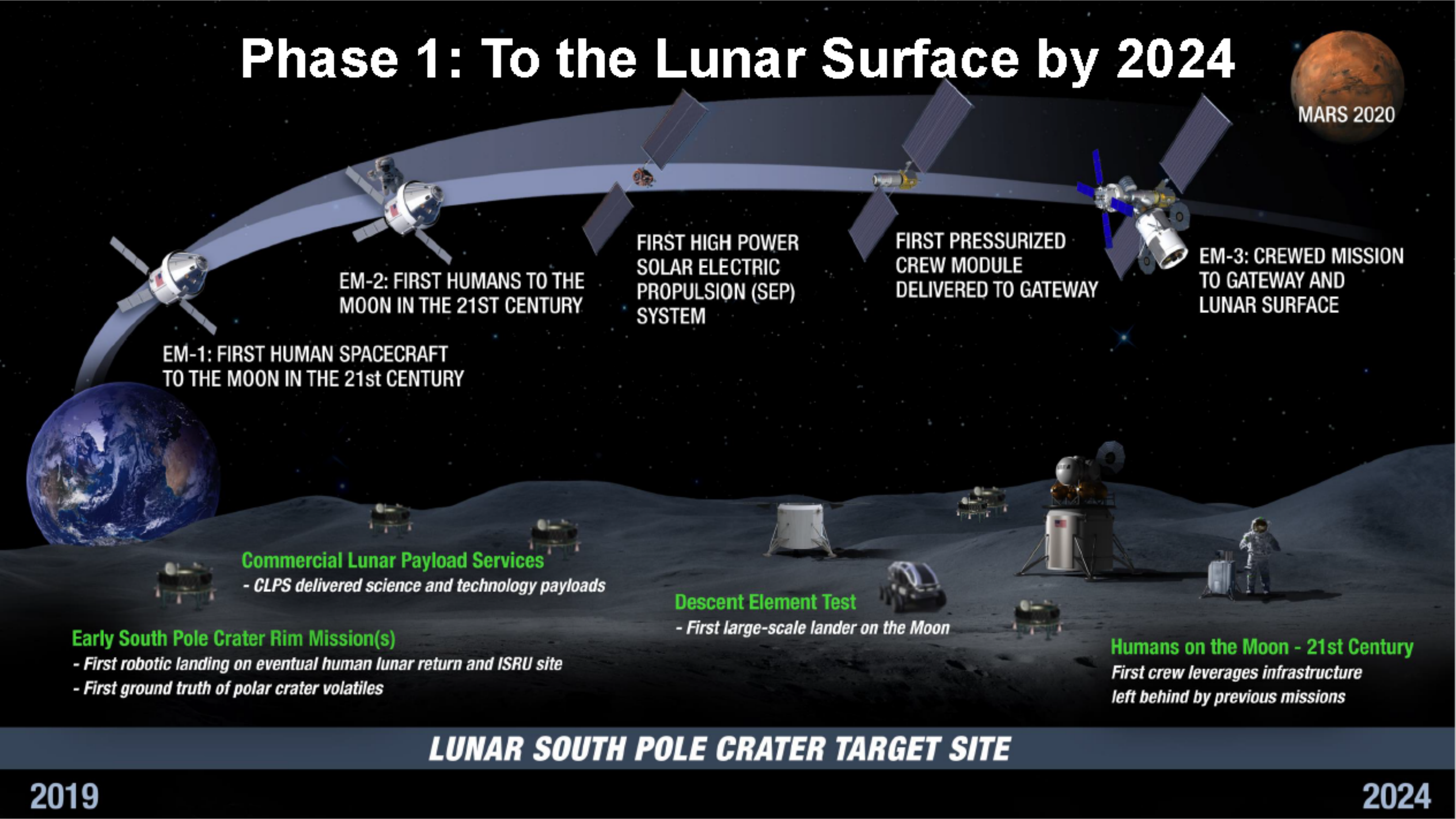


Excavation & Regolith Processing for O_2 Production



Refueling and Reusing Landers & Rovers




Phase 1: To the Lunar Surface by 2024
MARS 2020
EM-1: FIRST HUMAN SPACECRAFT TO THE MOON IN THE 21st CENTURY
EM-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
EM-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
Descent Element Test
- First large-scale lander on the Moon
Humans on the Moon - 21st Century
First crew leverages infrastructure left behind by previous missions
LUNAR SOUTH POLE CRATER TARGET SITE
2019
2024

Science by 2024

Polar Landers and Rovers

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

Non-Polar Landers and Rovers

- Ability to explore scientifically valuable terrains not explored by Apollo.
  Examples include:
  - Land at a lunar swirl and make the first surface magnetic measurement
  - Visit young volcanic features such as Ina to understand volcanic evolution
- PI-led instruments - Discovery-class science such as geophysical network and visiting lunar volcanic region

EM1 – Cube Satellite Program

- Over a dozen satellites will be launch as part of EM1

Orbital Data

- Cubesats delivered by CLPS providers, or comm/relay spacecraft could acquire new scientifically valuable datasets
- Global mineral mapping (including resource identification), global elemental maps, improved volatile mapping

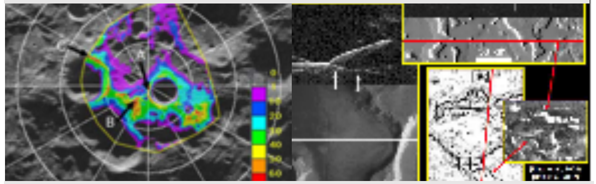
In-Situ Resource Initial Research

- What is the composition and ability to use lunar ice for sustainment and fuel

In Situ Resource Utilization (ISRU) Strategic Vector

Today
(Technology & Feasibility)

Significant Uncertainty with Water Resource



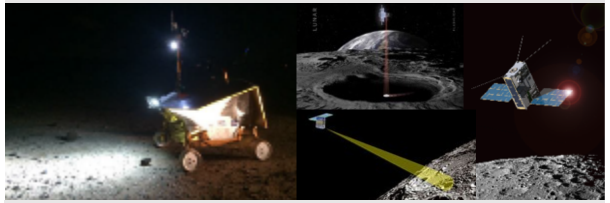
Technology/Concept Evaluation

Short Duration System Tests

Capability Feasibility Demonstrated

Near-Term
(Ground Dev. & Flight)

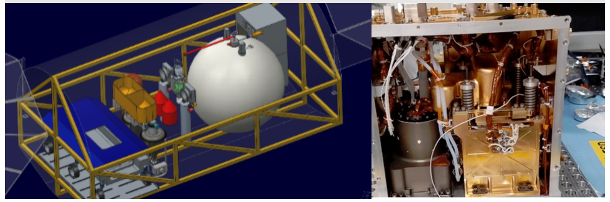
Resource & Water Characterization/Prospecting



Environmental & Long-Duration Ground Testing

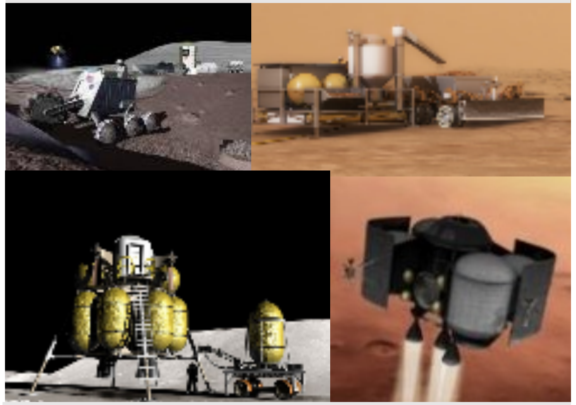
Technology Selection & System Development

Flight Demonstrations & Pilot Plants for Mission Enhancement

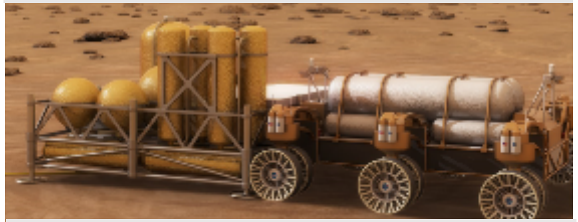


Goal
(Mission Utilization)

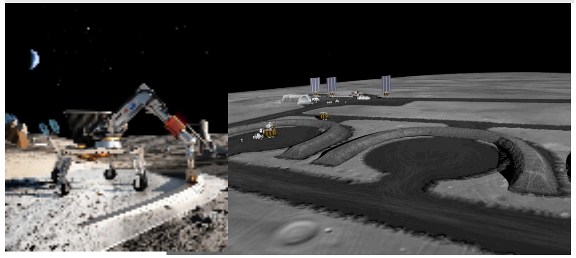
Oxygen & Propellant Production for Transportation



Consumables for Regenerative Power & Life Support



Manufacturing & Construction w/ In Situ Derived Materials



Sustainability at the Moon and on to Mars

- The U.S. leading in exploration and setting the standards for the Moon
- Unbound potential for partnerships and collaboration
- Meaningful, long-duration human missions
- Testing exploration operations that will be used for Mars
- Repeatable operations traveling from Earth to the Gateway to the surface with reusable systems
- Unprecedented science outside of Earth's influence
- Maintains strategic presence as a deep space port and refueling depot around the Moon
- Increases international and commercial partnership opportunities, fostering healthy competition

Goals for Initial and Long Term Lunar ISRU Consumable Production

HEOMD – Human Lunar Lander Reusability and Sustainability

- Early ISRU: Make **10 mT/yr oxygen** from lunar regolith to fuel lander **by 2030** if not sooner
- Sustainable ISRU: Mine **15 mT/yr** water in polar craters to fuel reusable landers by **TBD**

STMD – Strategic Technology Formulation

- Meet strategic thrusts for *Go, Land, Prosper* by addressing Key Capability Challenges for Regolith to Oxygen, Lunar Ice to Water, and Water to Cryogenic Propellant

SMD – Lunar Science and Resource Understanding

- Utilize Commercial Lunar Payload Services (CLPS), instruments, and missions to advance understanding of the Moon, especially volatiles in permanently shadowed regions at the poles for science and exploration

American Leadership and Commercialization of Space

- Promote *SPD-1: Reinvigorating America's Human Space Exploration Program* to lead an innovative and sustainable program of exploration with commercial and international partners (for long-term exploration and utilization of space resources)

Lunar ISRU Development & Incorporation Approach

ISRU Ground Development

- Develop and advance ISRU technologies to **TRL 5/6 through ground demonstration in relevant environment**
- Utilize Multi-center collaboration with a portfolio that includes internal NASA work, external contracts, and collaborative agreements/partnerships
- Where appropriate, develop lunar ISRU components and subsystems with a Mars-forward application
- Engage industry through public-private partnerships to lay the foundation for long-term lunar and space economic development and advance terrestrial industries

Flight Demonstration Path to Operational ISRU

- Utilize small demonstrations with near off-the-shelf hardware to obtain critical information quickly on lunar resources and operations
- Demonstrate critical technologies and processes that interact with lunar materials and environments
- Assess and characterize water and volatiles in lunar polar shadowed regions and craters
- Perform ‘pilot plant’ demonstrations at architecture relevant scales and durations to reduce the risk for ISRU-provided products for critical human mission applications

ISRU must first be demonstrated on the Moon before it can be mission-critical.

Lunar ISRU Mission Consumables: Oxygen from Regolith vs Polar Water

- **Oxygen from Regolith**
  - **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**
  - **Cannot be incorporated into the architecture from the start with low-moderate risk**
  - **Provides 100% of chemical propulsion propellant mass**
  - **Polar water is "Game Changing" and enables long-term sustainability**
    - Strongly influences design and resue of cargo and human landers and transportation elements
    - Strongly influences location for sustained surface operations

➢**Recommendation:** Pursue both for near-term needs and long-term sustainability

- Pursue oxygen extraction to meet near term needs (support humans 2029 goal)
- Pursue water extraction technology development for long term sustainability

Oxygen from Regolith

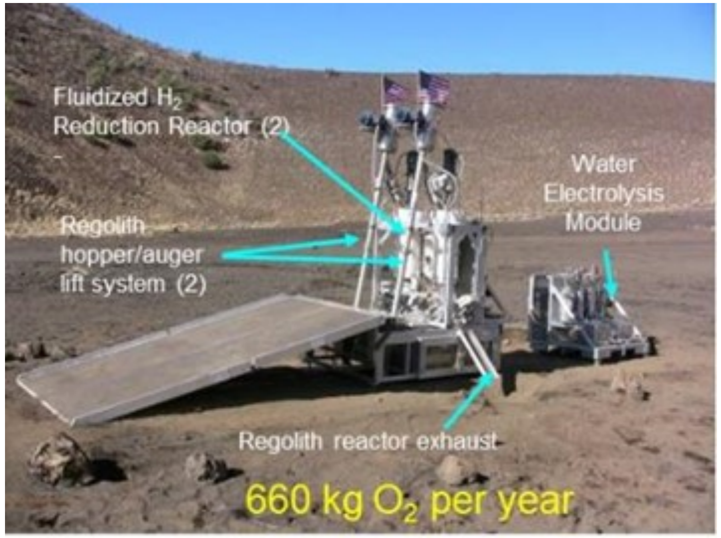
Oxygen from Regolith Mineral Oxides Background

- **Over 20 processes have been identified to extract the oxygen**
  - Required components range from TRL 3 to TRL 9
  - Typically, as processing temps increase, O_2 yield increases, and technical and engineering challenges increase

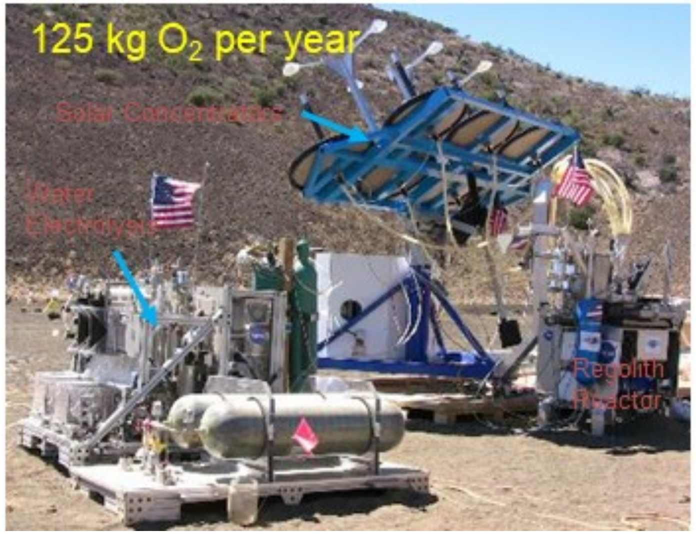
- **Work during the Constellation Program focused on three processes**
  - Hydrogen reduction: ‘low’ temperature, low yield (1 to 3 wt%), higher TRL
  - Carbothermal reduction: ‘higher’ temperature, medium yield (5 to 15 wt%), medium TRL
  - Molten regolith electrolysis: ‘high’ temperature, high yield (>20 wt%), low TRL

- **Two processes developed to TRL 4-5 at human mission relevant scale**

Scale up, Long-duration, & Environmental Testing Required



Hydrogen (H_2) Reduction



Carbothermal (CH_4) Reduction

Oxygen from Regolith Mineral Oxides – Comparison & Current Priority

	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

Carbothermal Reduction

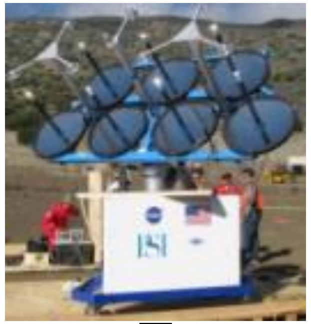
- Mix carbon into molten regolith at >1650 °C to extract oxygen in the form of carbon monoxide/dioxide
- Requires secondary reactor to convert CO / CO_2 to H_2O

Pros:

- **Will work on regolith anywhere on the Moon**; silicates are very abundant, especially at the Poles
- Higher yield (5 to 15 wt%) reduces excavation and transportation requirements

Cons:

- High temperature and thermal energy drives need for direct thermal technology (such as solar concentrators)



Solar Concentrator

Mobile Excavator

Inlet Hopper & Transfer

Carbothermal System

Water Electrolysis & Gas Storage

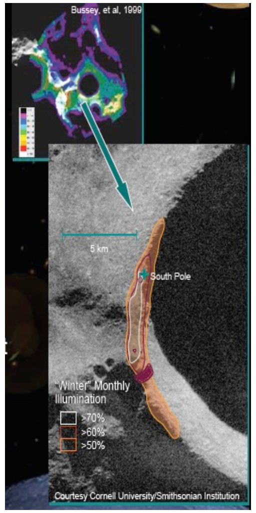
Liquefaction & Cryogenic Storage

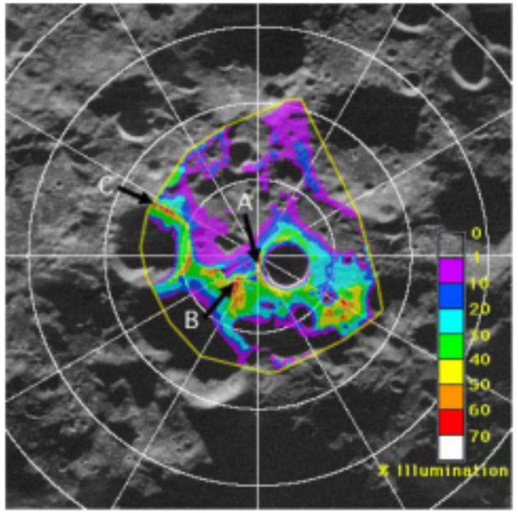
Lunar Polar Water Mining

Polar Water/Volatiles and Location

Polar Locations – *Optimal location for sustained surface operations*

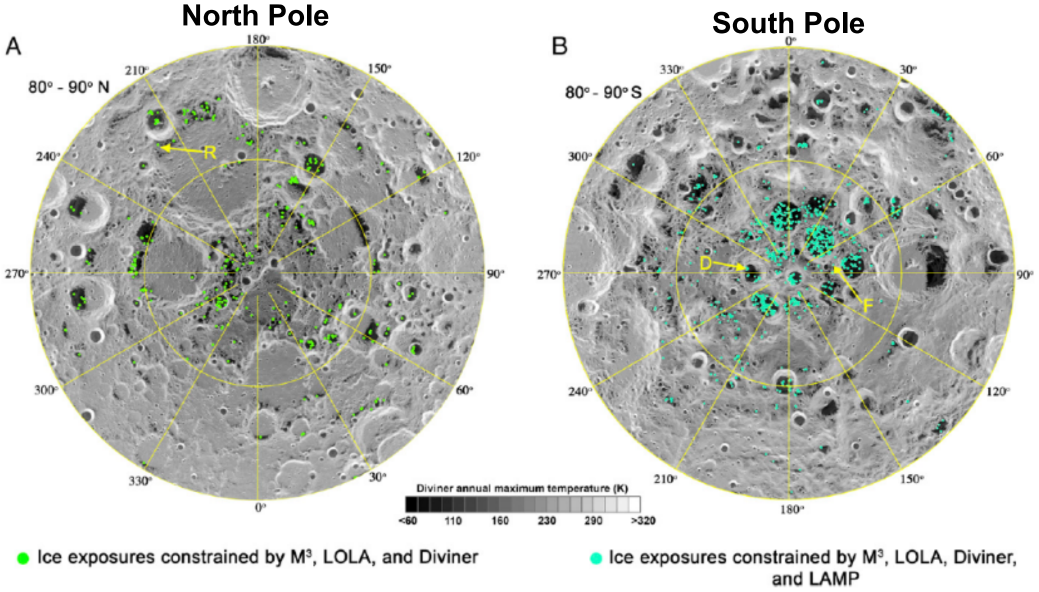
- Areas of near permanent sunlight (>70% sunlight per year)
  - Lower thermal extremes and greater use of solar power
  - **Regolith based resources for oxygen and metals**; Highland regolith (iron poor)
- Areas of permanent shadow
  - Cold locations for cryogenic storage, instruments, and thermal energy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





Polar Water/Volatiles

- LCROSS Impact estimated **5.5 wt%** water in plume
  - 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 M³ and LOLA data for the North pole, and M³, 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.



Significant Uncertainties Exist in Polar Resource Physical Properties and Distribution

Lunar 'ground truth' data is critical

Lunar Polar Water Extraction Architecture Options

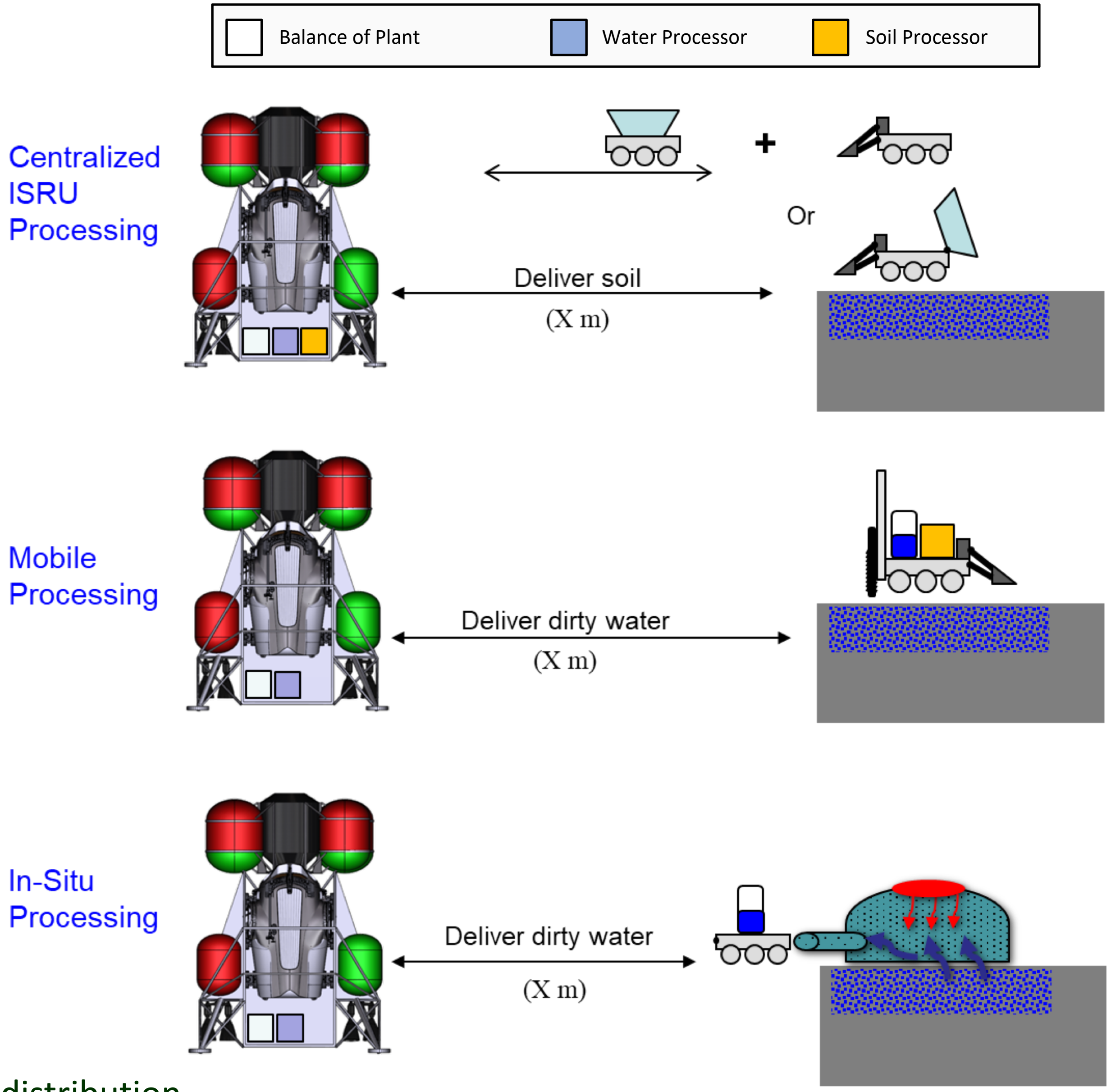
Lunar Polar Water Mining requires:

- Assessable resources in permanently shadow region (PSR)
- Nearby long-duration sunlit area for ISRU and human mission infrastructure
- Sustained communications with Earth (direct or relay)
- Architecture options involve what hardware/operations are performed in PSR

1. ISRU plant: Water extraction hardware is co-located with rest of ISRU plant
   - Water-ladened raw material is repeatedly transported out of the PSR
2. Mobile: Water extraction hardware is mounted on the mobile platform
   - Extracted (dirty) water is transported out of the PSR
3. In-situ: Water is removed from the soil without excavating soil
   - Extracted (dirty) water is transported out of the PSR

'Best' Architecture is predicated on

- Mining site selected: resource location and infrastructure location
- Resource properties: hardness and resource concentration, depth, and distribution



Polar Water Mining Option Comparison

- **At least 8 concepts are currently being explored including:**
  - Excavation w/ Auger dryer
  - Heated coring auger
  - Microwave heating
  - Heated Dome

- **Application of concepts are highly dependent on:**

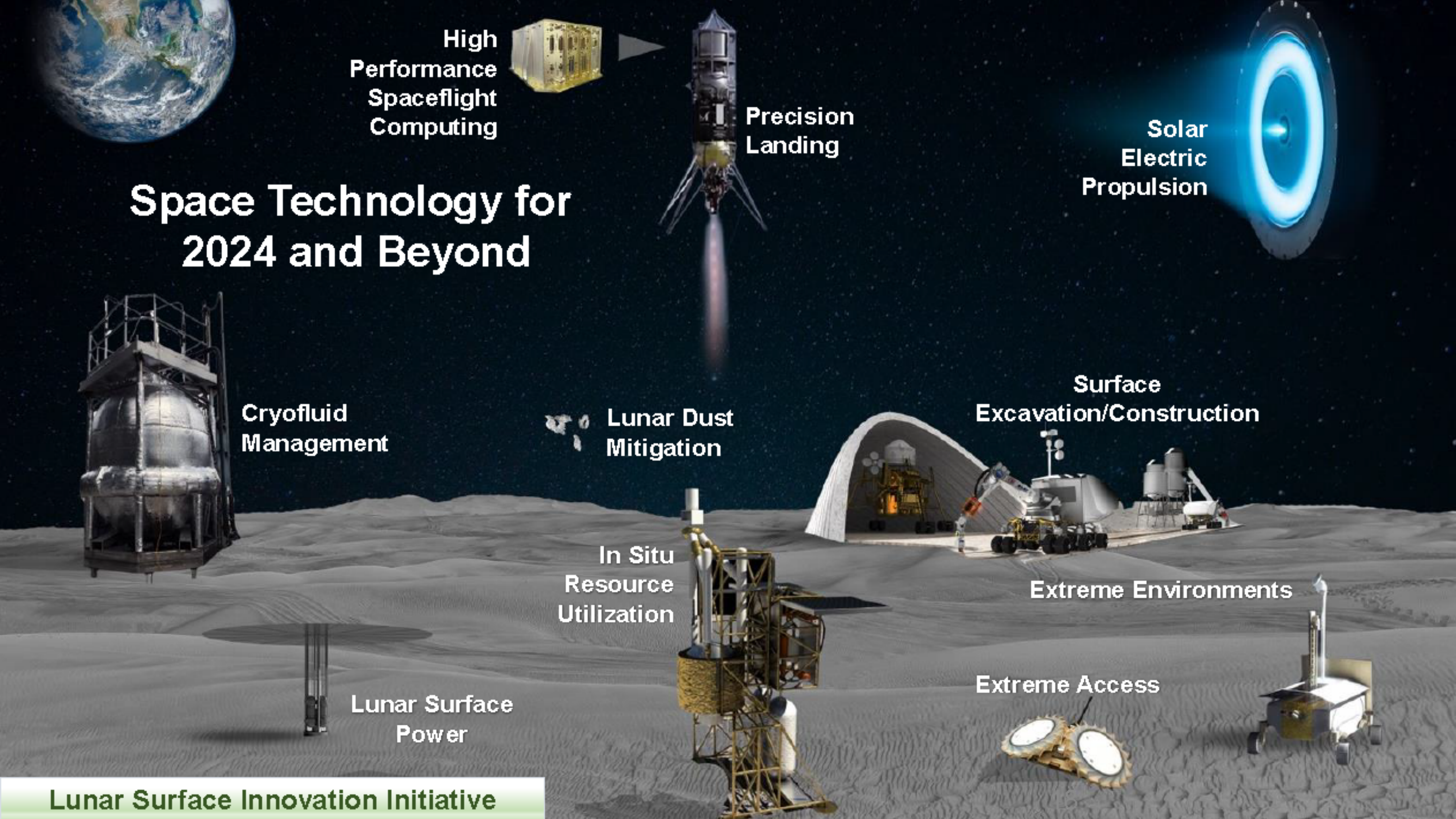
  Resource Depth Access: How deep the water resource can be for a given concept to work.

  Spatial Resource Definition: Defines the spatial resolution of the resource location needed for successful deployment.

  Volatiles retention: How much of the volatiles in the raw material are captured vs lost to the environment.

  Material Handling: How much interaction is required with the regolith.

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


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

Backup Charts

Polar Water Extraction and Processing Options