Space Exploration, Space Resource Utilization, & Terrestrial Applications

Presented at the

Space Travel: Adaptive Research and Technologies Conference

Nov. 18, 2019

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The STAR Tech conference is focused on:

- Bringing in non-traditional technologies from biological and chemical engineering including materials science, that apply to space travel technology and capability needs
- Accelerating the development of commercial and non-commercial space exploration and increase the intersection between terrestrial and space applications

The four major tracks this conference will highlight are:

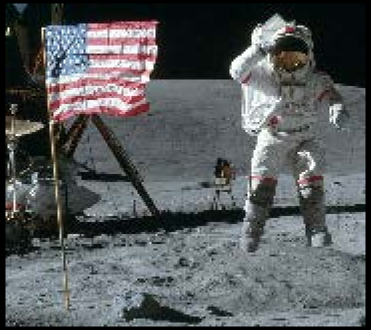
1. **Brewing** - This topic area will focus on how to develop fermentation for the production of useful molecules to support a sustainable presence on Earth and in space.
2. **Nourishing** - This topic area will focus on sustainable strategies of producing nutritious and palatable foods with the dual purpose of supporting food security on Earth and optimal crew health in space.
3. **Building** - This topic area will focus on developing new chemical, biological, and material science approaches to building components and techniques, for feasible survival in space and sustainable survival on Earth.
4. **Reclaiming** - This topic area will focus on chemical, biological, and material technologies that optimize resource utilization through reuse and reprocessing of existing "waste" streams.

Why We Explore Space Has Evolved Over Time

- Why Explore: It's What Humans Do!
- National Pride, International Prestige
- Scientific Advancement, New Insights
- Encourage International Cooperation, Global Partnerships
- Security, Long-term Survival of the Human Species

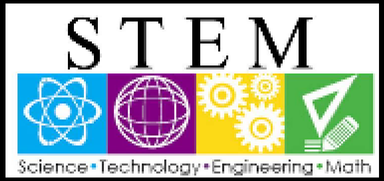
➢ Stimulate Economic Development & Expansion

➢ Make Life Better on Earth







How We Explore Space Has Evolved Over Time

Government-Led and Funded

Commercial Partners – Products & Services to Low Earth Orbit


Cargo


Crew


Habitats


Satellite Servicing

Commercial-Led


Orbital Tourism & Research

Suborbital Tourism & Research


Lunar/Mars Business & Colonization

Commercial Partners – Products & Services Beyond Earth Orbit


Cargo

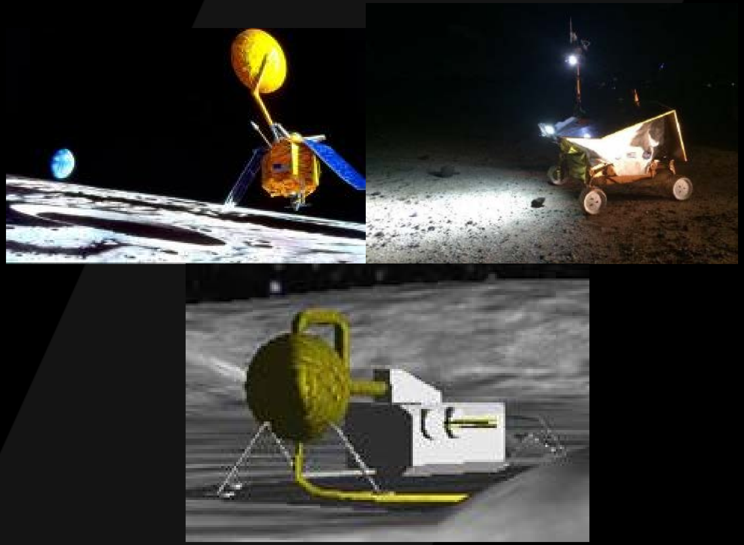

Crew


Propellant


Mining

Space Resource Utilization: Make it Don't Take it!

Finding & Mining Lunar Water & Volatiles



Excavation & Regolith Processing for Oxygen & Metal Production

Synthetic Biology for Consumables & Manufacturing

Construction of Landing Pads, Berms, Roads, and Habitats

In Space Manufacturing

Recycling, Trash Conversion & Processing

Why Use Space Resources?

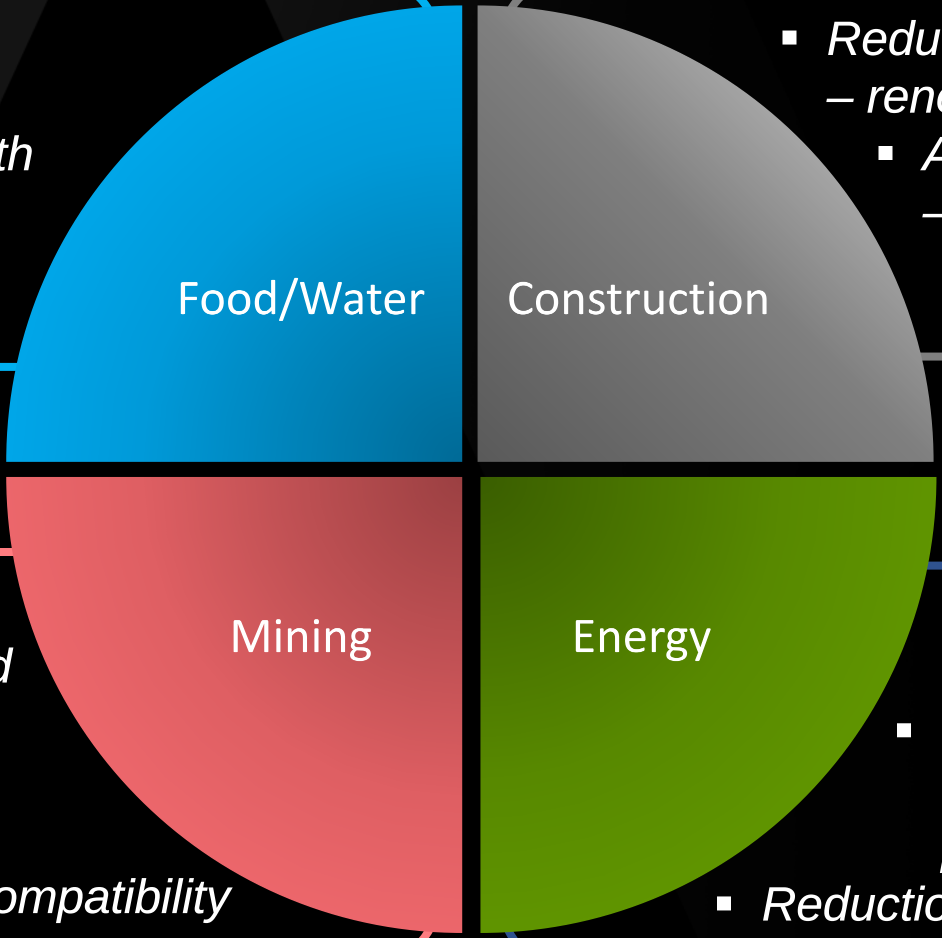
- **Using Space Resources can reduce mission and architecture mass and costs**
  - Launch mass savings
  - Reduce launch numbers
  - Supports reuse of mission transportation assets
  - Supports terrestrial industry/Enables space commercialization

- **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**

Space Resource Utilization Is Synergistic with Terrestrial Needs



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

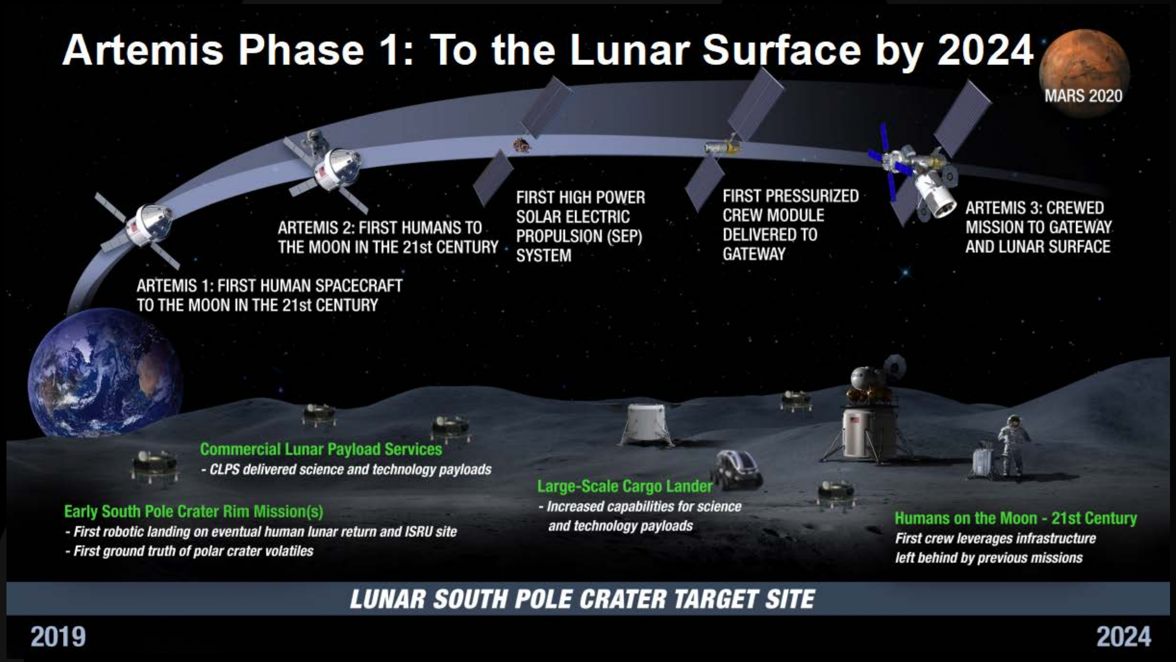
Construction
- *Reduce or eliminate cement and asphalt – renewable materials*
- *Alternative construction techniques – 3-D printing, no Portland cement*
- *Remote operation and automation*

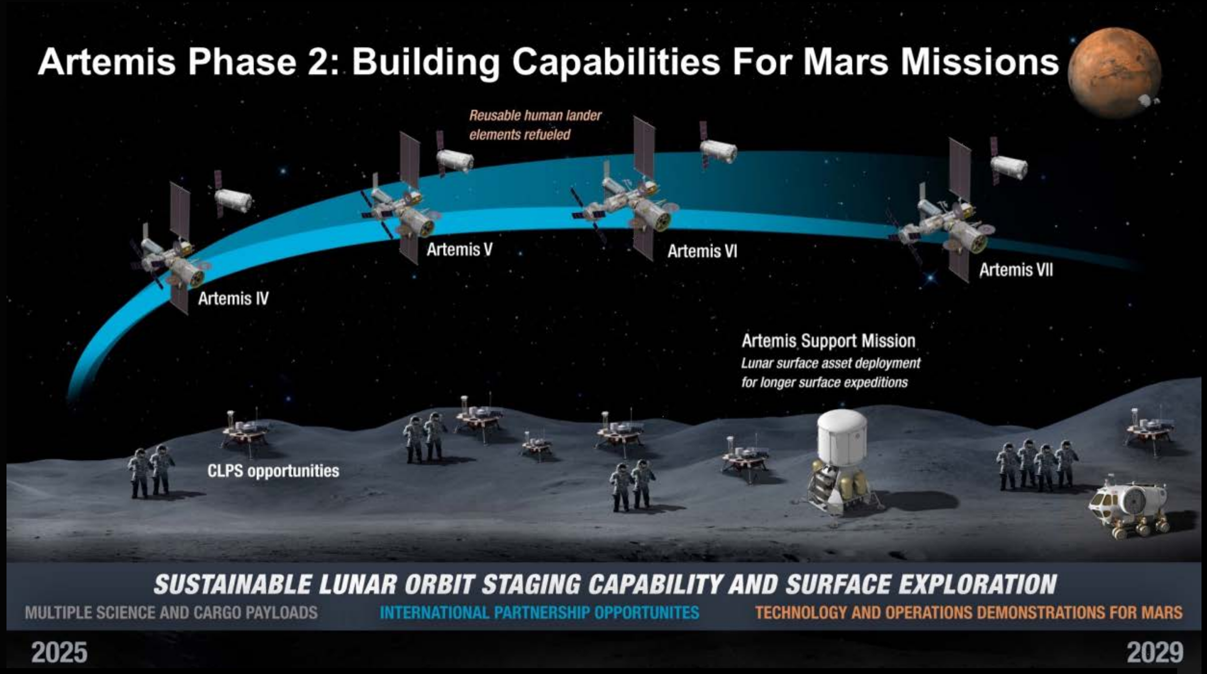
Mining
- *Increase safety*
- *Reduce maintenance and logistics*
- *Increase mining and processing efficiency*
- *Improve environmental compatibility*

Energy
- *More efficient power generation, storage and distribution*
- *Increase renewable energy: Use sun, thermal, trash, and alternative fuel production*
- *Reduction of Carbon Dioxide emissions*

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

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

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

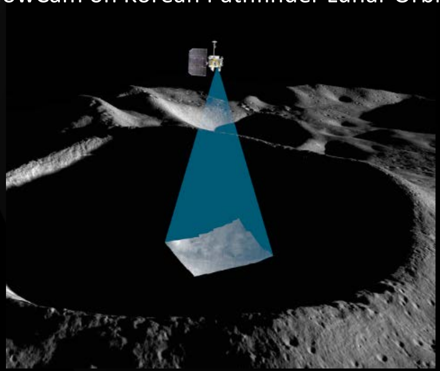
In-Situ Resource Initial Research

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

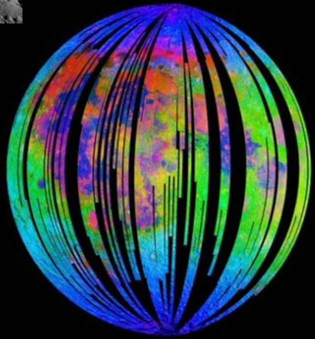
Lunar Science & Resource Prospecting

Orbital Missions

ShadowCam on Korean Pathfinder Lunar Orbiter



Lunar Trailblazer (Phase A)

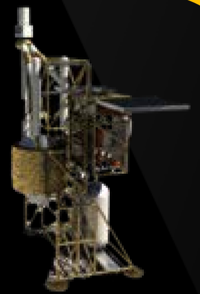


Surface Missions

Lunar Surface Innovation Initiative (LSII)

In Situ Resource Utilization

Collection, processing, storing and use of material found or manufactured on other astronomical objects



Surface Excavation/Construction

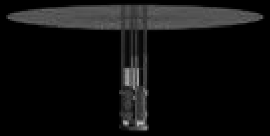
Enable affordable, autonomous manufacturing or construction

Lunar Dust Mitigation

Mitigate lunar dust hazards

Sustainable Power

Enable continuous power throughout lunar day and night



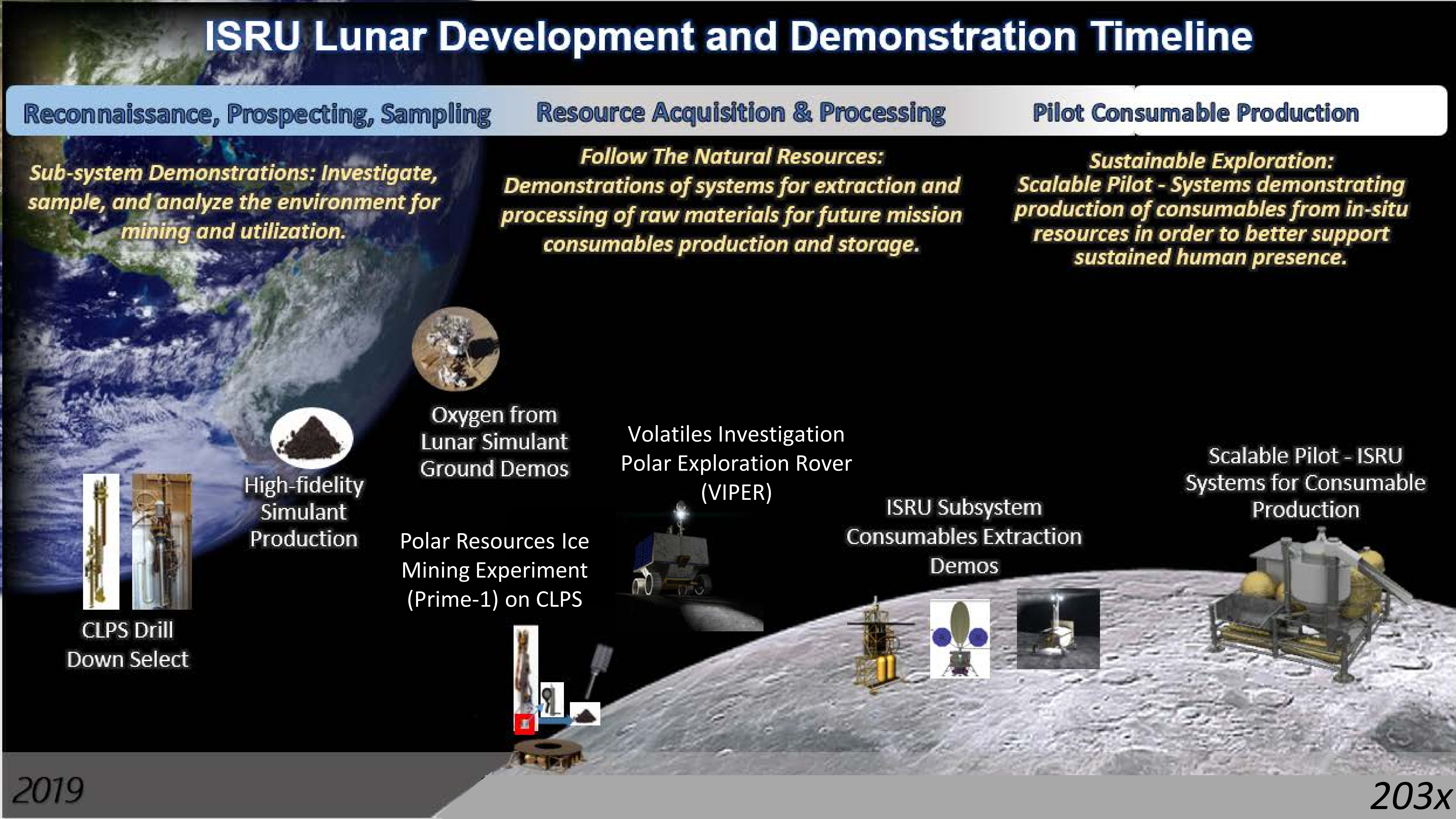
Extreme Access

Access, navigate, and explore surface/subsurface areas

Extreme Environments

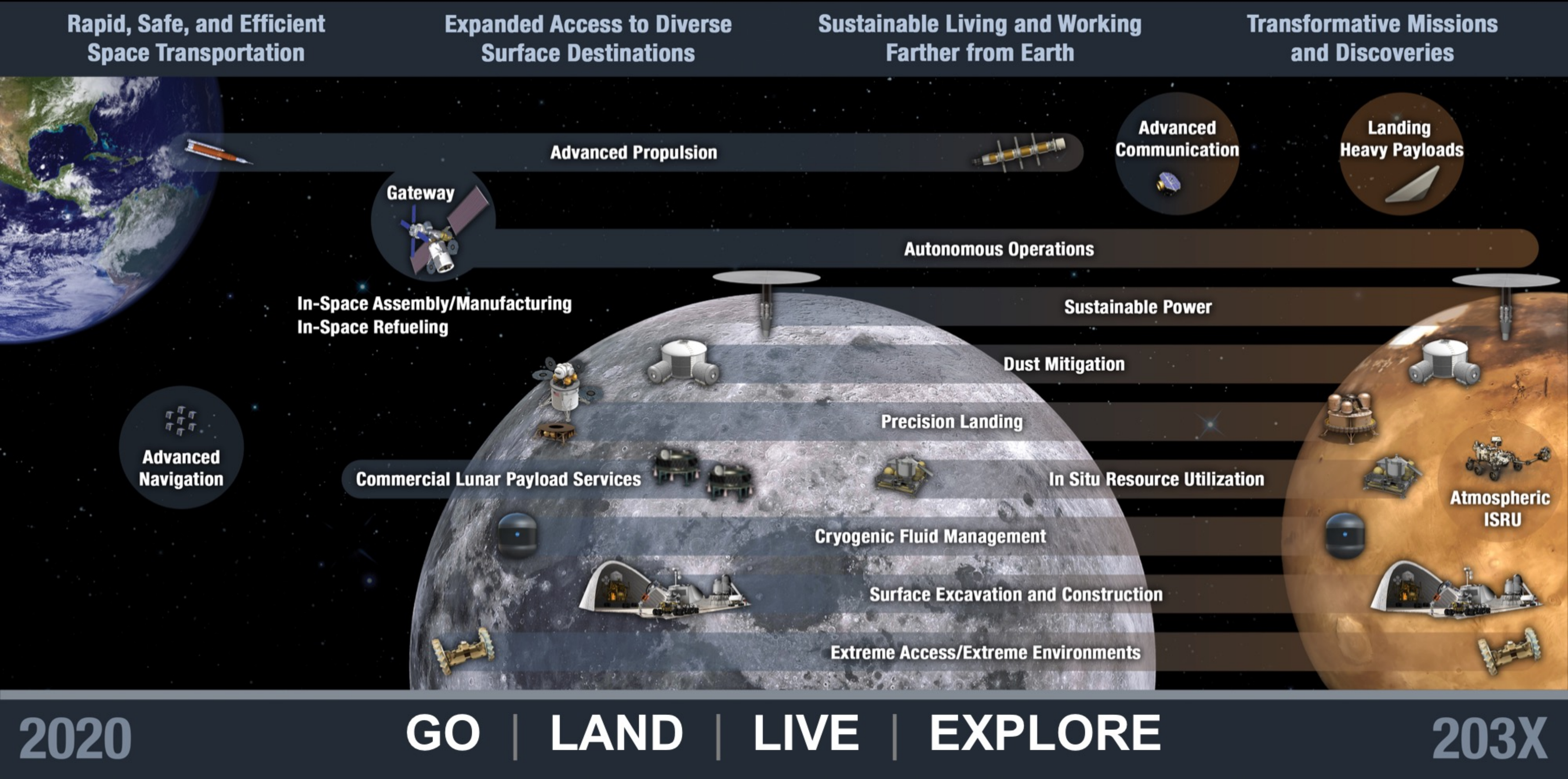
Enable systems to operate through out the full range of lunar surface conditions

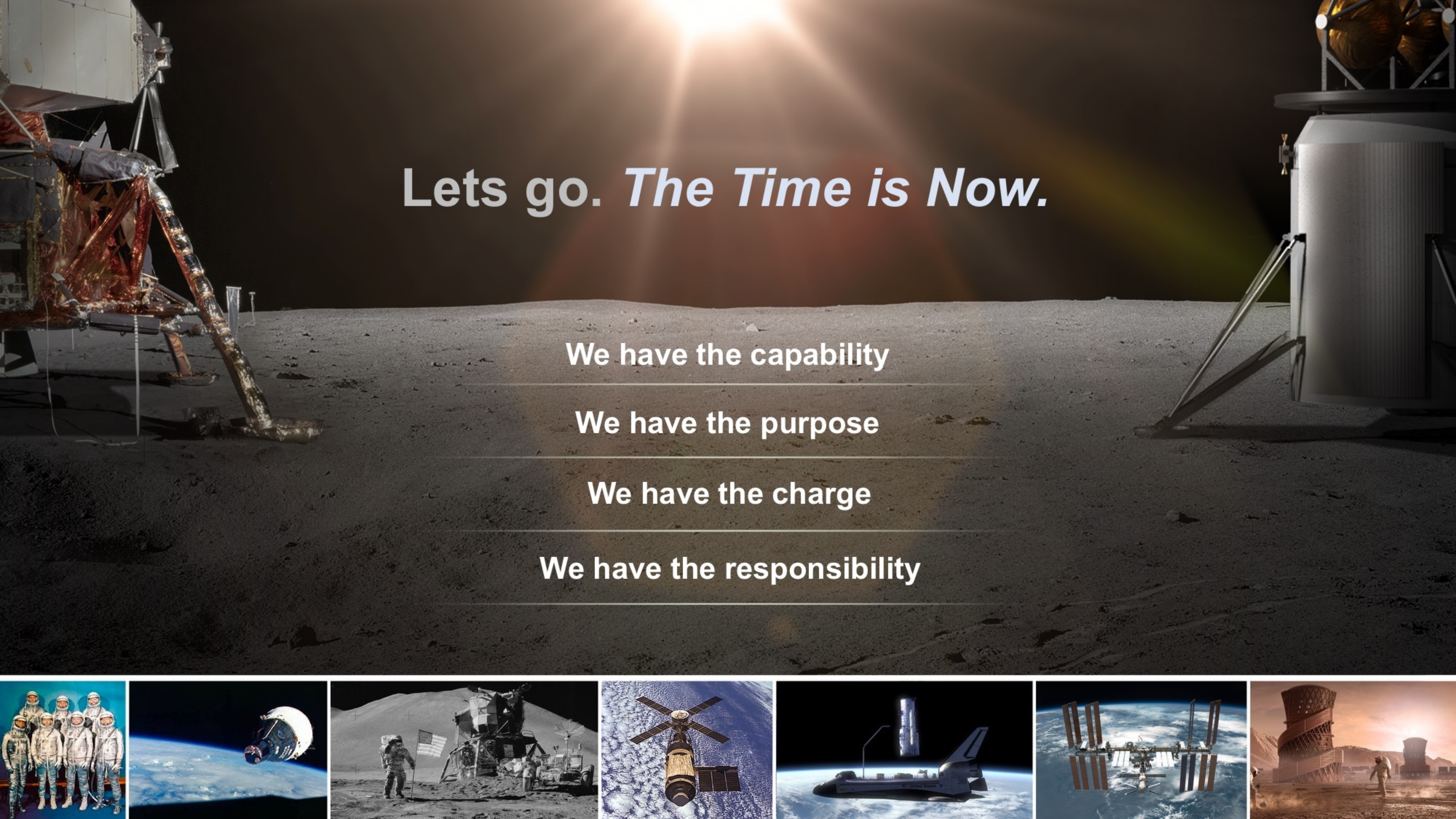
- LSII will develop the technologies required for establishing lunar infrastructure across these six primary capability areas.
- LSII will accelerate technology readiness for key components and systems and provide early technology demonstrations which will help to inform relative SMD activities and development of HEO crewed flight systems.
- HEOMD will focus on development of crewed flight systems for lunar exploration and operations, such as surface habitats, pressurized rovers for crew mobility, and advanced life support systems.



ISRU Lunar Development and Demonstration Timeline
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 from Lunar Simulant Ground Demos
Volatiles Investigation Polar Exploration Rover (VIPER)
Scalable Pilot - ISRU Systems for Consumable Production
High-fidelity Simulant Production
ISRU Subsystem Consumables Extraction Demos
Polar Resources Ice Mining Experiment (Prime-1) on CLPS
CLPS Drill Down Select
2019
203x

Reaching The Moon And Mars Faster With NASA Technology

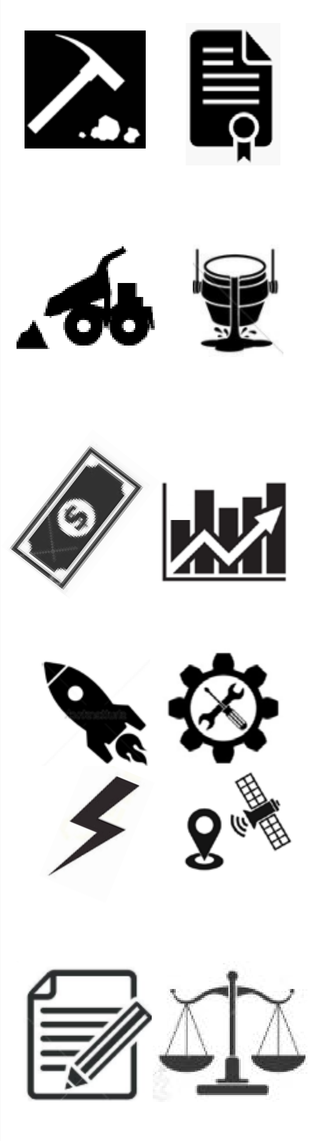



Lets go. *The Time is Now.*
We have the capability
We have the purpose
We have the charge
We have the responsibility

Backup

Barriers to Commercial Space ISRU Investment

Today: There is Neither a Production Capability or Market



Barriers

Resource Uncertainty
- Resource Exploration
- Reserve Estimation

Mining Technology Readiness
- Demonstrated Scale
- Demonstrated Operations

Customers
- Known users/market
- Market growth potential

Sustainable Operations
- Reliable/Cheap Transportation
- Logistics and Maintenance
- Infrastructure

Regulatory
- Legal Framework
- Product/Property Rights
- Standards
- Taxes

What Can/Should Be Done?

- Increase global resolution of resource information
- Campaign of resource exploration missions (Gov. & Industry)
- Agreement/standards for reserve estimation (ex JORC/NI43-101)

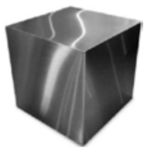
- Government/industry partnerships & space mining institute
- Spin-in/Spin-off Technologies into Terrestrial Applications
  - Incentives for insertion; greener/safer innovations
- Demonstrate technologies, production rate, and product quality

- 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

- Utilize additive manufacturing for high wear parts
- Governments help establish initial transportation, power, communication, and surface infrastructure
- Establish common interfacing standards

- Establish international agreements
- Establish stable legal and regulatory framework
- Establish tax incentives/flow-through shares
- Enable ownership enforcement

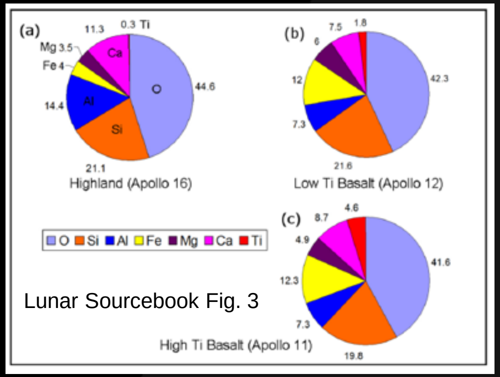
Main *Natural* Space Resources of Interest for Human Exploration

	 Moon	 Mars	 Asteroids	Uses
Water (Hydrogen) 	Icy Regolith in Permanently Shadowed Regions (PSR) Solar wind hydrogen with Oxygen	Hydrated Soils/Minerals: Gypsum, Jarosite, Phylosilicates, Polyhdrated Sulfates Subsurface Icy Soils in Mid-latitudes to Poles	Subsurface Regolith on C-type Carbonaceous Chondrites	▪ Drinking, radiation shielding, plant growth, cleaning & washing ▪ Making Oxygen and Hydrogen
Oxygen 	Minerals in Lunar Regolith: Ilmenite, Pyroxene, Olivine, Anorthite	Carbon Dioxide in the atmosphere (~96%)	Minerals in Regolith on S-type Ordinary and Enstatite Chondrites	▪ Breathing ▪ Oxidizer for Propulsion and Power
Carbon (Gases) 	▪ CO, CO_2, and HC's in PSR ▪ Solar Wind from Sun (~50 ppm)	Carbon Dioxide in the atmosphere (~96%)	Hydrocarbons and Tars (PAHs) in Regolith on C-type Carbonaceous Chondrites	▪ Fuel Production for Propulsion and Power ▪ Plastic and Petrochemical Production
Metals 	Minerals in Lunar Regolith ▪ Iron/Ti: Ilmenite ▪ Silicon: Pyroxene, Olivine, Anorthite ▪ Magnesium: Mg-rich Silicates ▪ Al: Anorthitic Plagioclase	Minerals in Mars Soils/Rocks ▪ Iron: Ilmenite, Hematite, Magnetite, Jarosite, Smectite ▪ Silicon: Silica, Phyllosilicates ▪ Aluminum: Laterites, Aluminosilicates, Plagioclase ▪ Magnesium: Mg-sulfates, Carbonates, & Smectites, Mg-rich Olivine	Minerals in Regolith/Rocks on S-type Stony Iron and M-type Metal Asteroids	▪ *In situ* fabrication of parts ▪ Electical power generation and transmission

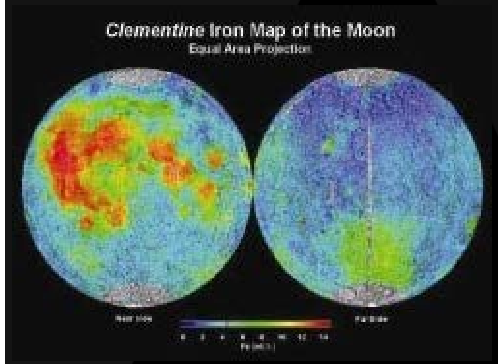
Note: Rare Earth Elements (REE) and Platinum Group Metals (PGM) are not driving Resources of interest for Human Exploration

Lunar Resources

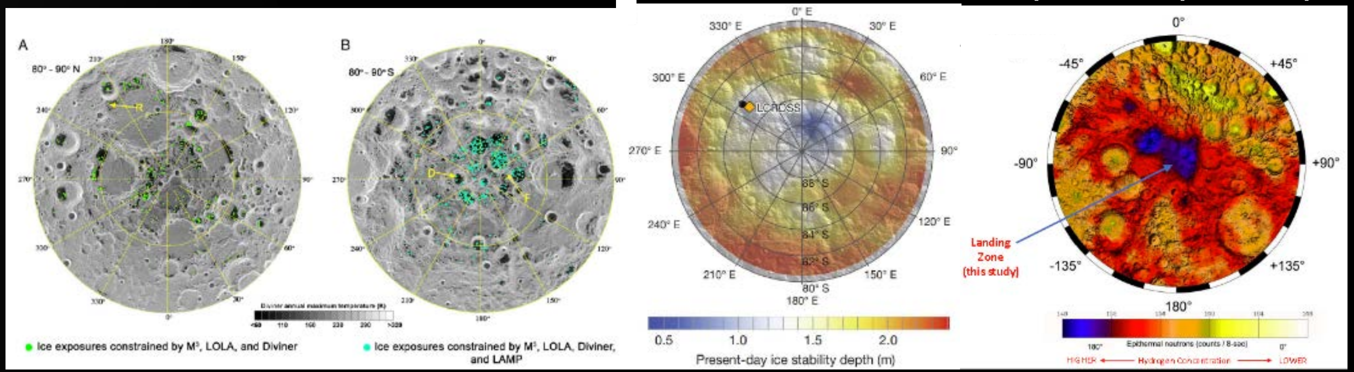
Regolith, Solar Wind Volatiles, Polar Water/Volatiles



Lunar Sourcebook Fig. 3



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**

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.