

National Aeronautics and Space Administration



NASA Fuel Cell and Hydrogen Activities

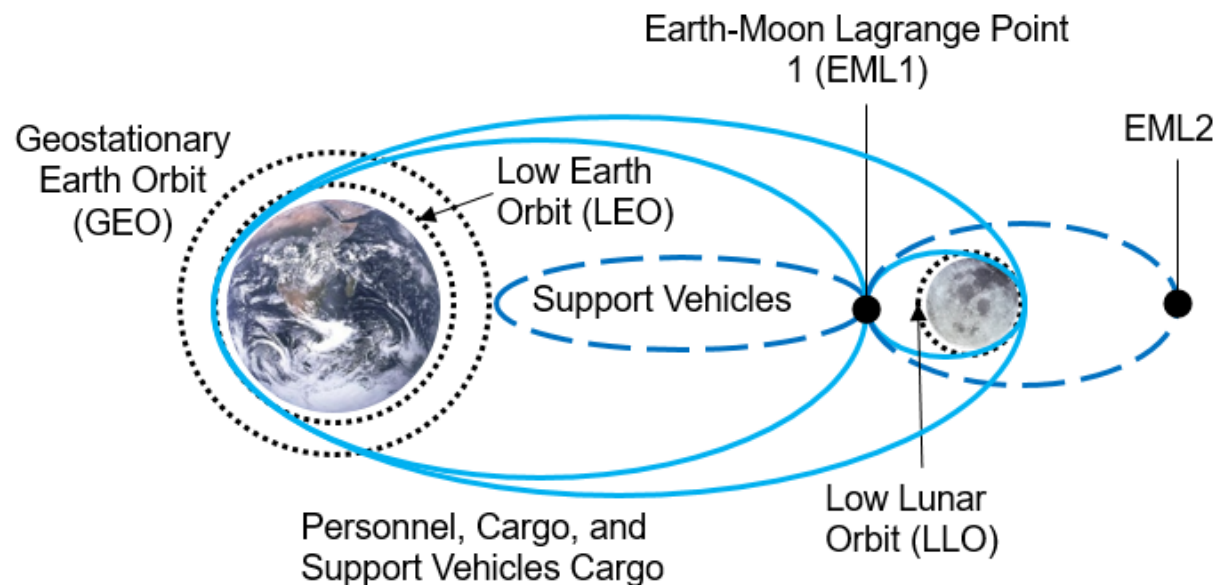
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NASA Glenn Research Center
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Presentation Overview



- NASA Exploration
- NASA Hydrogen Utilization
 - Production
 - Transfer and Storage
 - Consumption
- Summary





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Fluid and Cryogenic Systems Branch, Glenn Research Center*
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 - *Environmental Control and Life Support Systems (ECLSS) System Engineer,
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GO

LAND

LIVE

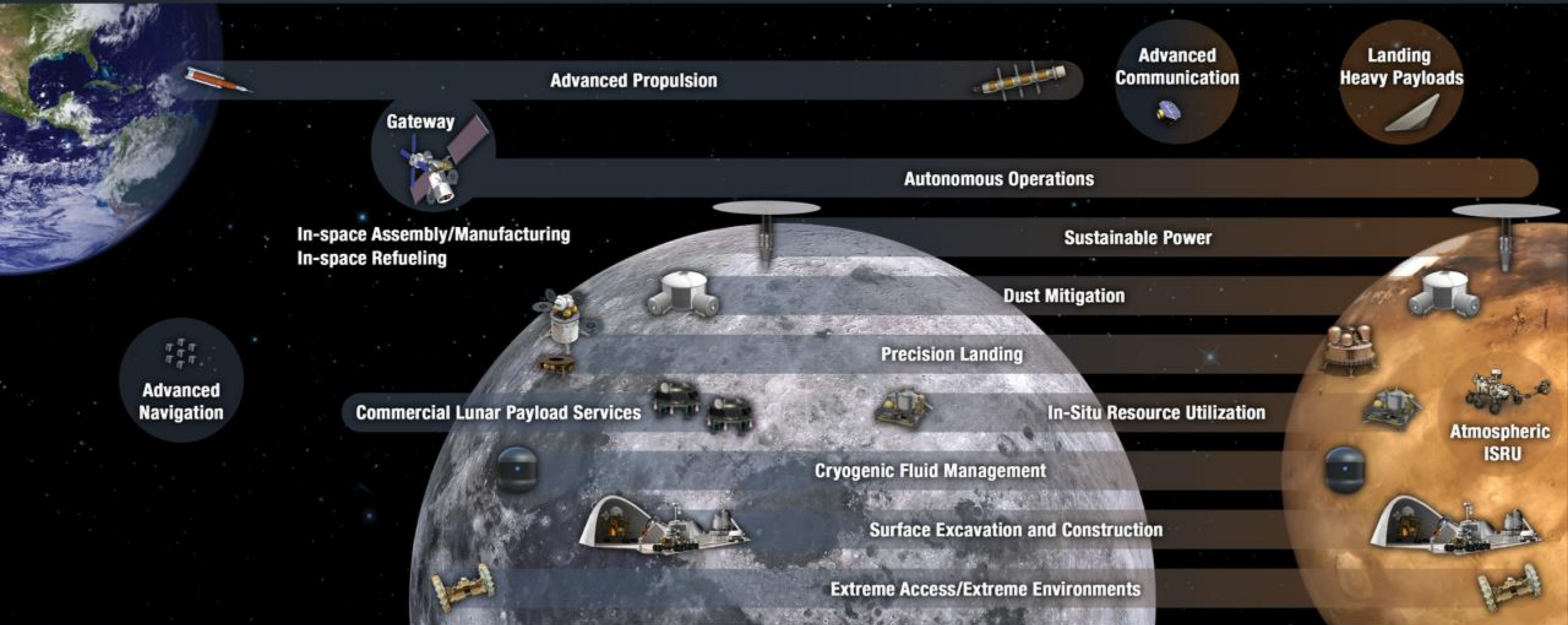
EXPLORE

Rapid, Safe, and Efficient
Space Transportation

Expanded Access to Diverse
Surface Destinations

Sustainable Living and Working
Farther from Earth

Transformative Missions
and Discoveries





We're going to the Moon to learn to live on other planets and for the benefit of all humanity.

With the Artemis lunar exploration program, NASA will put the first woman and first person of color on the lunar surface and build a sustainable presence there and in lunar orbit.

The Artemis Program Snapshot



Space Launch System



Commercial Lunar Payload Services



The Gateway in lunar orbit



Orion



First woman and first
person of color to the Moon

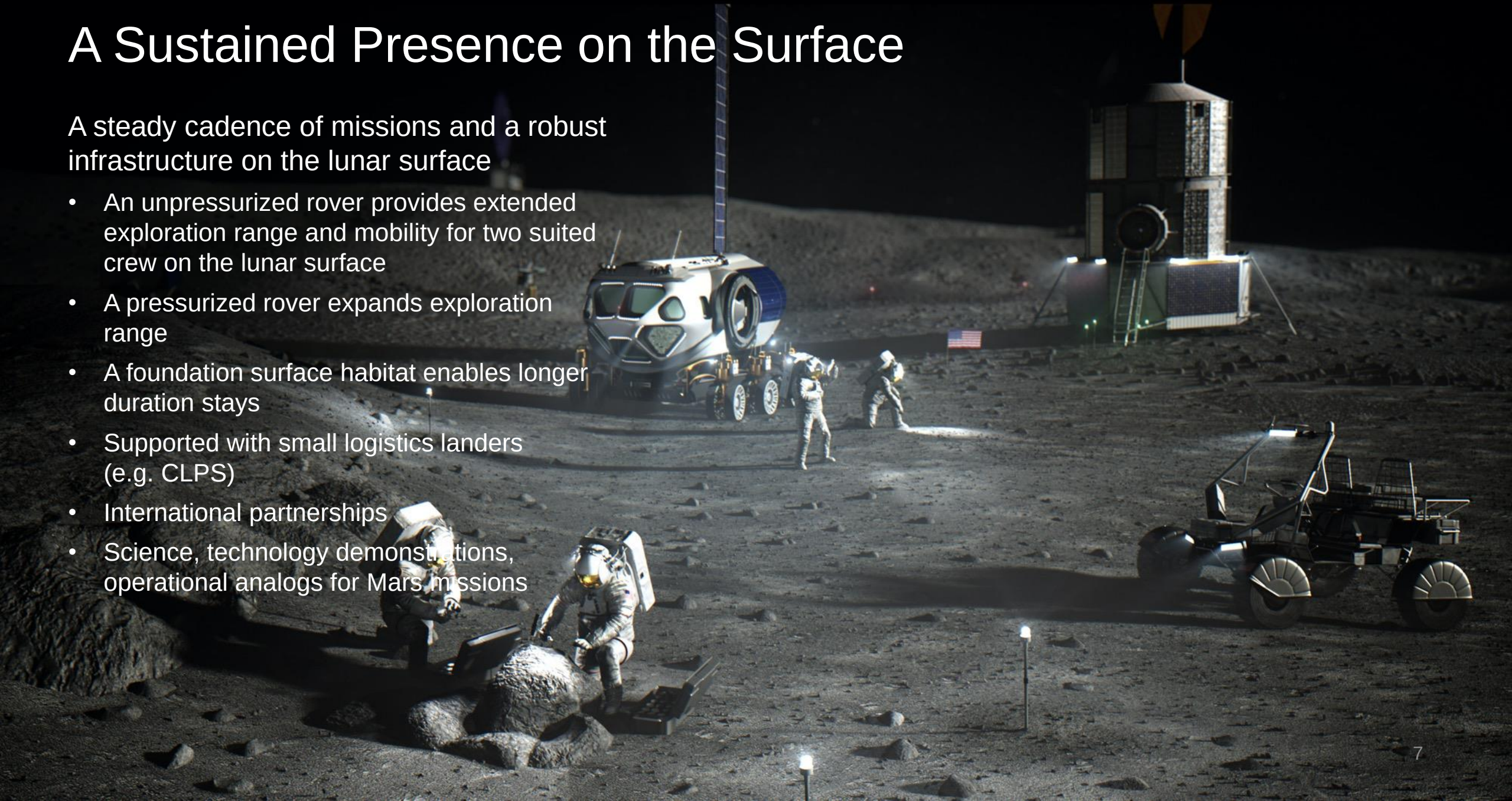


Surface systems

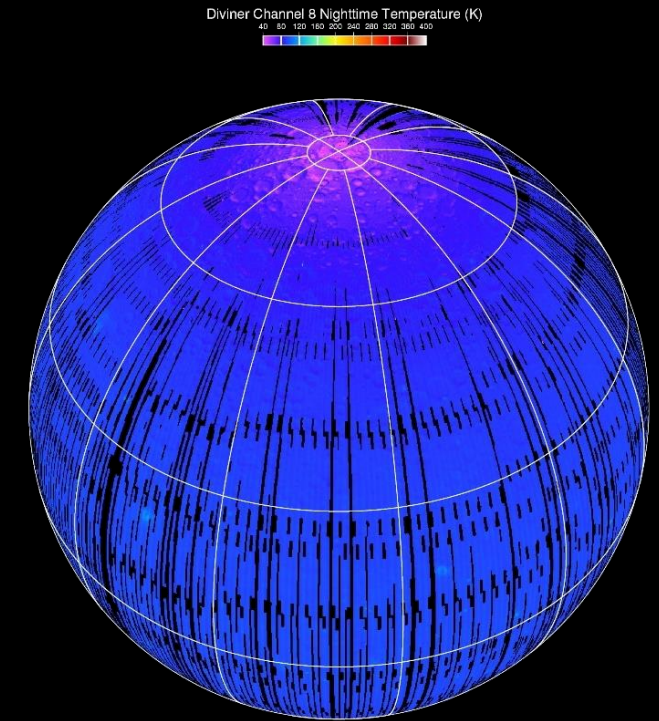
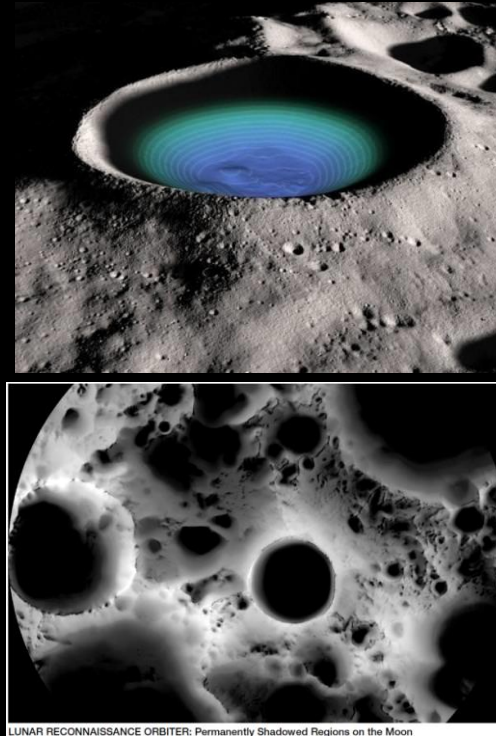
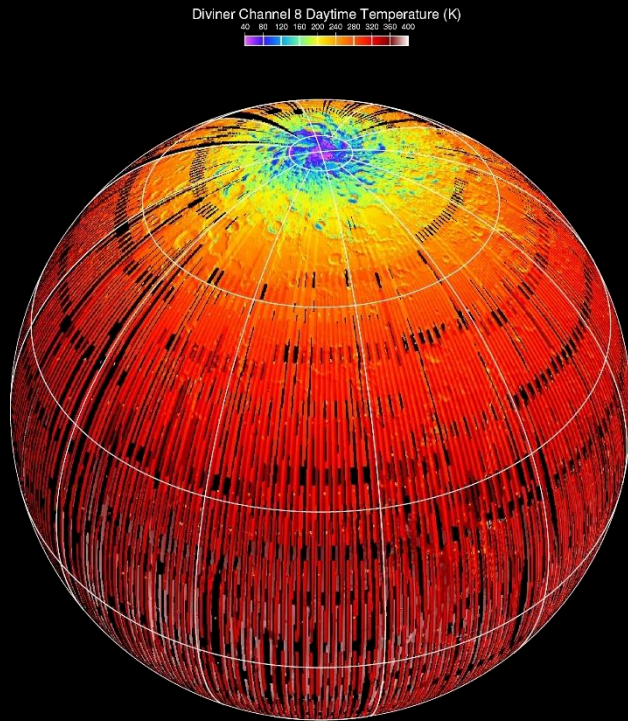
A Sustained Presence on the Surface

A steady cadence of missions and a robust infrastructure on the lunar surface

- An unpressurized rover provides extended exploration range and mobility for two suited crew on the lunar surface
- A pressurized rover expands exploration range
- A foundation surface habitat enables longer duration stays
- Supported with small logistics landers (e.g. CLPS)
- International partnerships
- Science, technology demonstrations, operational analogs for Mars missions



The Lunar Environment



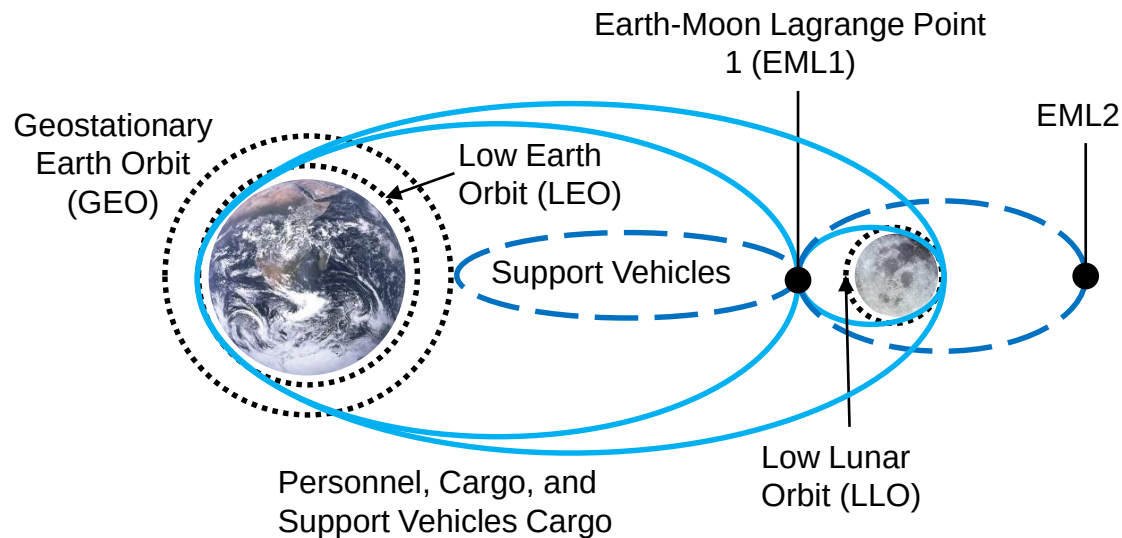
- The average temperature on the Moon (at the equator and mid latitudes) varies from 90 Kelvin (-298 °F or -183 °C), at night, to 379 Kelvin (224 °F or 106 °C) during the day.
- Extremely cold temperatures within the permanently shadowed regions of large polar impact craters in the south polar region during the daytime is at 35 Kelvin (-397 °F or -238 °C)
- Lunar day/night cycle lasts between 27.32 and 29.53 Earth days (655.7 to 708.7 hours)
- Regulating hardware in this environment requires **both power and energy**

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

- Enable exploration by staging required resources in forward locations
 - Earth Orbit (LEO, GEO)
 - LaGrange Points (EML1 and EML2)
 - Lunar Orbit
 - Lunar Surface
- Resources include propellant depots, propellant production facilities (initially H_2 and O_2), and consumable storage

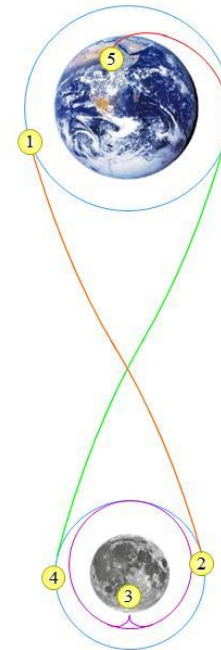


Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

- 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

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



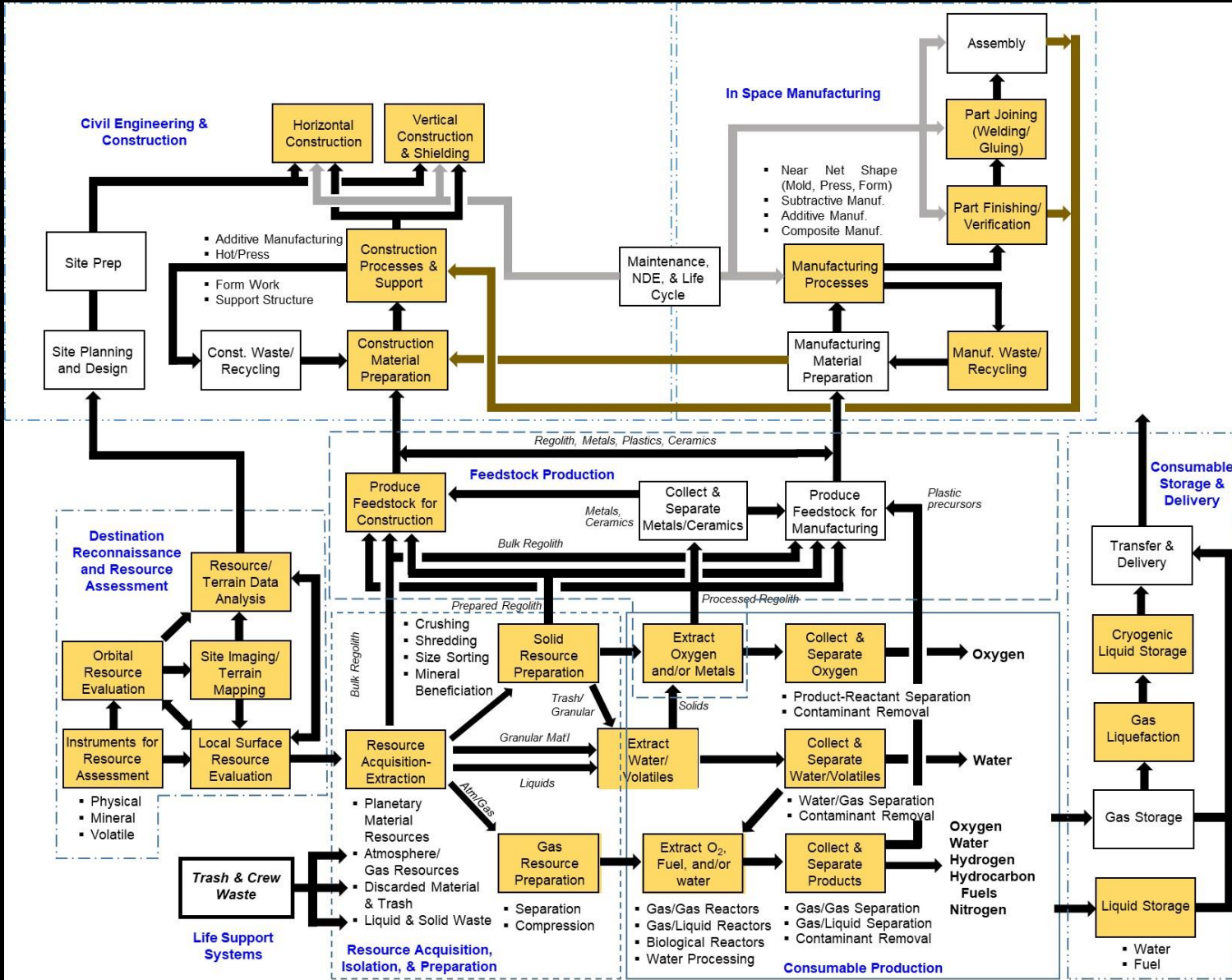
- 1 LEO
- 2 Lunar Destination Orbit
- 3 Lunar Surface
- 4 Lunar Rendezvous Orbit
- 5 Earth Surface

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

In Situ Resource Utilization (ISRU) on the Lunar Surface



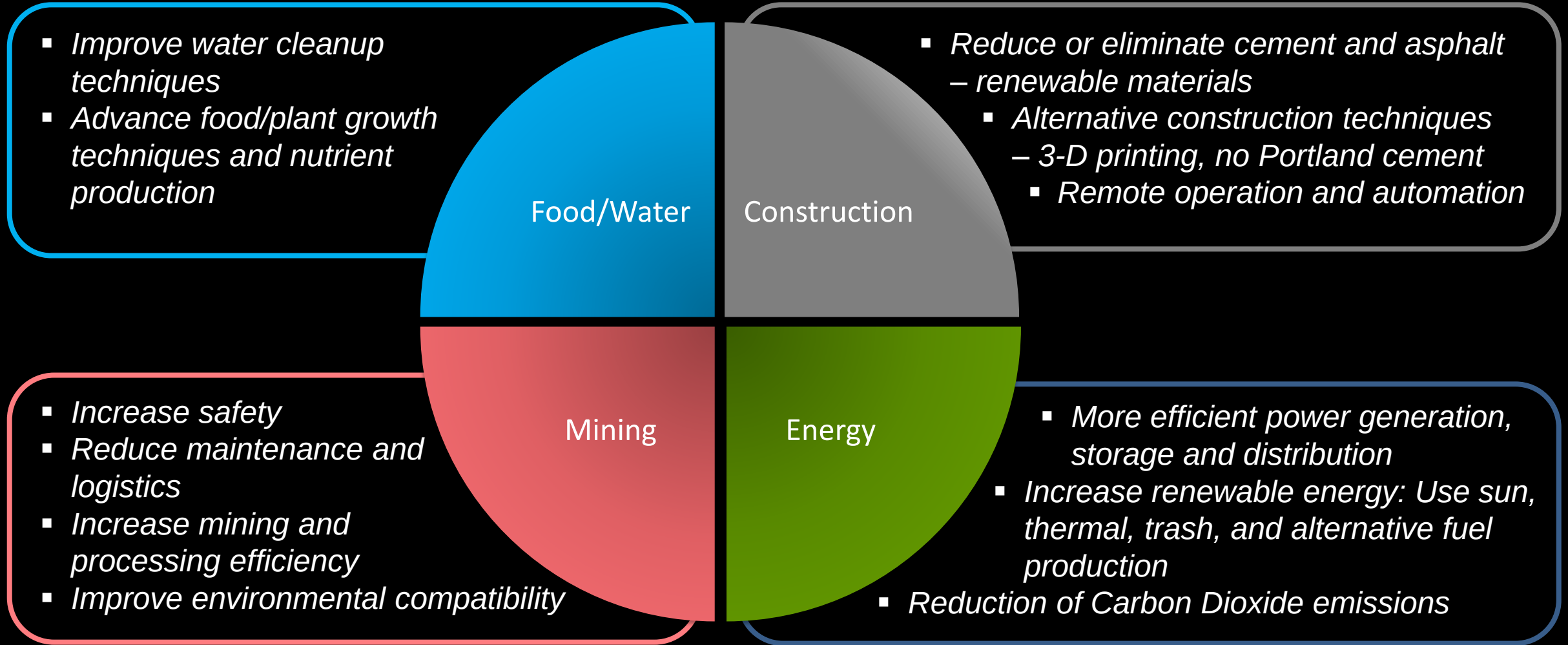
ISRU Functional Block Diagrams



Functional Block Diagrams

- Help understand connectivity (interfaces/requirements):
 - Internally
 - With other Technology Plans and Disciplines
 - Cross-cutting
- Focus assessment of technology options in each sub-function
 - Used for technology and gap assessments
- Understand influence of technologies on complete system

ISRU Synergistic with Terrestrial Needs



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

POWER to explore the

LUNAR SURFACE

Hydrogen and Fuel Cells are an integral part of a Lunar Surface Power Architecture



Hydrogen and Fuel Cells for Lunar Exploration

- Fuel cells can provide energy storage to provide power in locations near humans where nuclear power may not be an option
- Regenerative fuel cell can provide continuous power for longer-term operations (such as the lunar night)
- Hydrogen enables energy storage and transportation in the challenging lunar environment

Hydrogen Activities Within NASA



Hydrogen Generation

- *Electrochemically dissociating water into gaseous hydrogen and oxygen*
 - *Environmental Control and Life Support Systems (ECLSS)*
 - *Energy Storage*
 - *ISRU*
 - *Contaminated Water Sources (ISRU)*
- *Recover raw materials from local sources*
 - *Water (ice) Mining*
 - *Contaminated Water Processing*
 - *Regolith Processing*

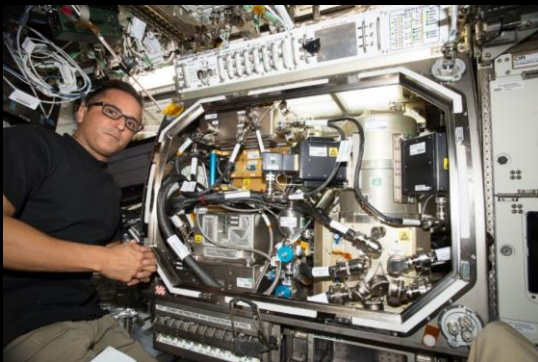


Hydrogen Transfer and Storage

- *Hydrogen Management in space*
 - *Cryogenic Fluid Transfer in μ -gravity*
- *Extend storage duration of cryogenic fluids*
 - *Zero-Boil-off Tanks*
 - *High-efficiency Efficiency Cryo-coolers*

Hydrogen Consumption

- *Propellants*
 - *Launch Vehicles*
 - *Mars/Lunar Landers*
- *Fuel hydrogen-based fuel cells*
 - *Lunar/Mars surface systems*
 - *Urban Air Mobility*
- *Metal Processing*
- *Refrigerants*



Hydrogen Generation

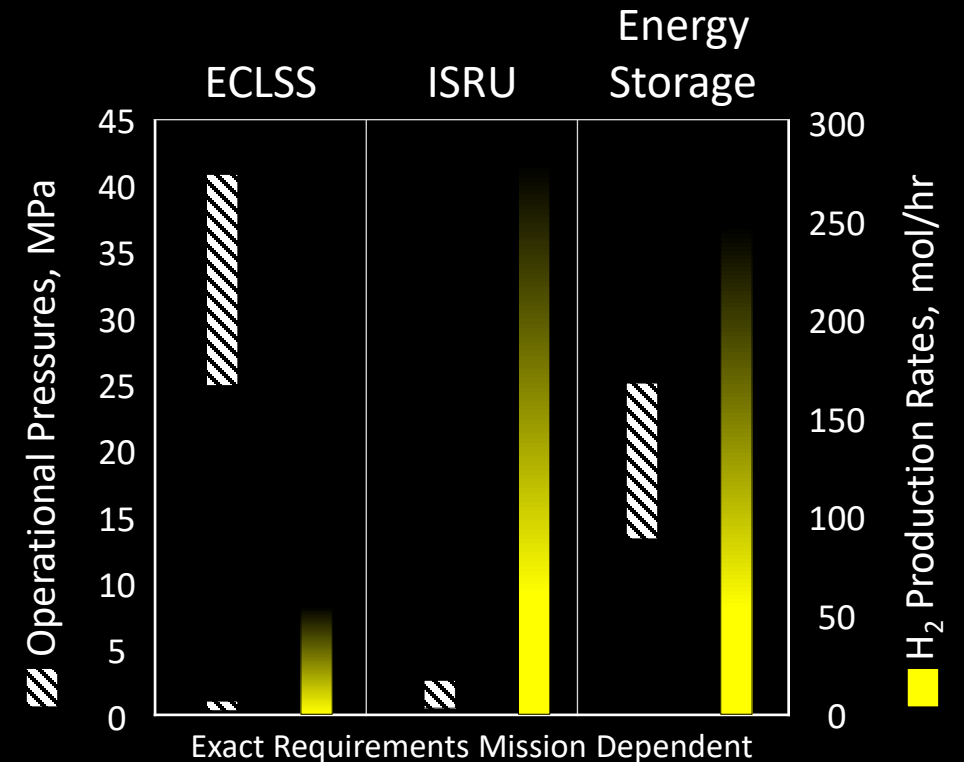
Electrolysis

- Electrochemically dissociate water into gaseous hydrogen and oxygen
- ECLSS
 - Unbalanced Design ($H_2 \ll O_2$)
 - Unmet long-term requirements for reliability, life, or H_2 sensors stability
- Energy Storage
 - Balance Design ($H_2 \approx O_2$)
 - Unmet long-term requirements for performance, reliability, life, sensors availability, sensor stability
- ISRU
 - Balance Design ($H_2 \approx O_2$)
 - Unmet long-term requirements for performance, reliability, or life
 - Tolerate contaminated water sources to minimize pre-conditioning requirements

Water Mining and Processing

- Recover raw materials from local sources
 - Regolith Processing
- Contaminated Water Processing
 - Minimize water cleaning system complexity and mass
 - Remove inert contaminants (e.g. Ca^+ and Mg^+ salts)
 - Remove chemically active contaminants (e.g. H_2S , NH_3 , H_2CO_3 , H_2SO_4 , Hg, Methanol, etc.)

Notional Electrolysis Requirements





Hydrogen Generation

Current Reactant Production and Processing Activities:

1. Proton Exchange Membrane (PEM) Electrolysis

- ISS Advanced Oxygen Generator Assembly (AOGA)
- Regenerative Fuel Cell Project
- High Pressure PLSS O₂ Tank Recharge
- **IHOP PEM Water Electrolysis/Clean-up – Paragon**
- **Lunar Propellant Production Plant (LP3) – Skyre**

2. Solid Oxide Electrolysis (SOE)

- **Lunar Ice Processing – CSM/OxEon**
- **Production of Oxygen and Fuels from In-Situ Resources on Mars – OxEon**
- **Redox Tolerant Cathode for Solid Oxide Electrolysis Stacks – OxEon**
- **Robust and Reversible Metal-Supported Solid Oxide Cells for Lunar & Martian Applications – NexTech and Washington St. Univ.**
- **Reversible Protonic Ceramic Electrochemical Cells (RePCEC) – Special Power Sources and Kansas State University**

3. Alkaline (Dirty Water) Electrolysis

- **Advanced Alkaline Electrolysis (AAE) – Teledyne**
- **Advanced Alkaline Reversible Cell (AARC) – pH Matter**
- **Bifurcated Reversible Alkaline Cell for Energy Storage (BRACES) – pH Matter**

4. Water Recovery and Processing

- Polar Resources Ice Mining Experiment-1 (PRIME-1)
- Resource Recovery with Ionic Liquid for Exploration (RRILE)
- Molten Regolith Electrolysis (MRE)
- **ISRU-Water Electrolysis Trade Study - Collins Aerospace**
- **Production of Oxygen and Fuels from In-Situ Resources on Mars (O2PM) - OxEon Energy LLC**
- **Enhancing Lunar Exploration with ISRU Strategies Study - Blue Origin**
- **Integrated Architecture Trade Studies on ISRU Technologies for Human Space Exploration - University of Illinois**
- **Carbothermal Reduction Reactor Design - Sierra Nevada Corp.**
- **Carbothermal Reactor Risk Reduction Testing and Analytical Model Development - Sierra Nevada Corp./Orbitec**
- **Redox Tolerant Cathode for Solid Oxide Electrolysis Stacks - OxEon Energy, LLC**
- **Helium and Hydrogen Mixed Gas Separator - Skyhaven Systems, LLC**

Funding Sources

NASA Funds	BAA
Tipping Point / ACO	SBIR / STTR

Hydrogen Transfer and Storage

Transporting Hydrogen through cis-lunar space is complicated

Variable Storage times

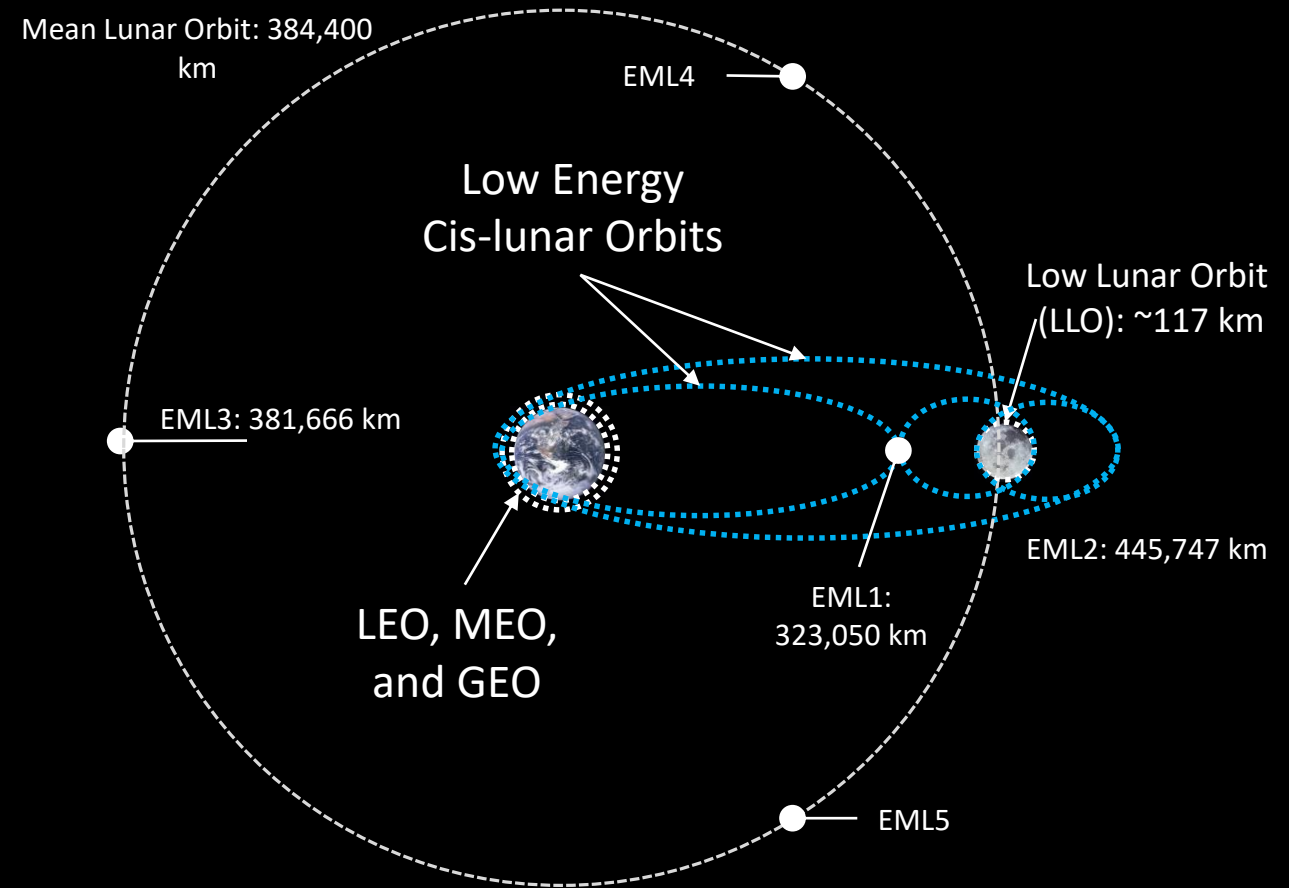
Supply vehicle can launch days to months before target vehicle

No buoyancy to help separate the cryogenic fluids from evolved gases

Complex multi-phase fluid flow

Complex Thermal Environment

Very large temperature differences between sun-facing and deep-space facing surfaces
Radiation only available heat sink
Challenging to pre-cool target system while retaining cryogenic fluids within the system



Lagrange Points of the Earth-Moon (EM) System as viewed from above the Earth-Moon Orbital Plane

Image Not to Scale

Hydrogen Transfer and Storage

Current cryogenic activities:

1. Cryogenic Propellant Production and Storage

- Demonstration of benefits of MLI and Vapor Cooling with hydrogen (SHIIVER)
- Two stage cooling (90 K and 20 K) of a liquid hydrogen tank
- Demonstration of radio frequency mass gauging in hydrogen
- Ground demonstration of hydrogen liquefaction and storage – Blue Origin
- Lunar Propellant Production Plant (Hydrogen and Oxygen) – Skyre
- 20 K and 90 K cryocooler development – NASA/Creare
- Combined hydrogen/oxygen refrigeration systems

2. Cryogenic Propellant Management and Transfer

- Space Launch System ground and flight systems
- Transfer of densified (sub-atmospheric) hydrogen into a flight-like tank
- Develop and test coupler prototypes for refueling spacecraft – > 8 different approaches (combination of funding sources)
- Human Landing System development for in-space and lunar landing systems – SpaceX/Blue Origin/Dynetics
- In-space demonstration mission using liquid hydrogen – Lockheed Martin
- Demonstration of a smart propulsion LOX/LH2 cryogenic system on a Vulcan Centaur upper stage testing precise tank pressure control, tank-to-tank transfer, and multi-week propellant storage – ULA



Funding Sources

NASA Internal	BAA
Tipping Point / ACO	SBIR / STTR

Hydrogen Consumption



Propellants

- NASA currently requires between 3 to 10 million pounds LH_2 per year but likely to increase with launch cadence
- KSC and SSC require 5 to 12 commercial tankers / day during LH_2 fill to minimize schedule impacts
- Space Launch Systems (SLS)
 - 539,000 gal LH_2 capacity
 - Burn rate is $\sim 67,375$ gal LH_2 /min
- Commercial Cis-Lunar Transportation industry estimated to need $\sim 50,000$ to $\sim 275,000$ kg LH_2 /year



The Space Launch System rocket core stage comes alive during the Green Run hot fire test on 16 Jan. 2021 at NASA's Stennis Space Center near Bay St. Louis, Mississippi.

Image Credit: NASA

Fuel hydrogen-based fuel cells

- Lunar/Mars surface systems
 - ≤ 10 kW primary fuel cell modules fueled by H_2/O_2 or CH_4/O_2
 - $36 \text{ kW}\cdot\text{hr}_{\text{net}}$ to $1 \text{ MW}\cdot\text{hr}_{\text{net}}$ H_2/O_2 regenerative fuel cell systems
- Urban Air Mobility
 - Multiple air-based primary fuel cell systems studies for systems fueled by H_2 , CH_4 , and bio-fuels (e.g. X-57)
 - Hydrogen storage technologies for aircraft (e.g. CHEETAH)



NASA's all-electric X-57 Maxwell prepares for ground vibration testing at NASA's Armstrong Flight Research Center in California.

Credits: NASA Photo / Lauren Hughes



Hydrogen Consumption

Current Hydrogen Consumption Activities:

1. Proton Exchange Membrane (PEM) Fuel Cells

 - Regenerative Fuel Cell Project
 - Advanced Modular Power and Energy System (AMPES) – Infinity Fuel Cell & Hydrogen
 - Hydrogen Electrical Power System (HEPS) – Teledyne
 - Lunar Lander Fuel Cell (LLFC) – Blue Origin
2. Solid Oxide Fuel Cells (SOFC)

 - Surface Power Generation from Lunar Resources and Mission Consumables - Precision Combustion
 - Highly Efficient, Durable Regenerative Solid Oxide Stack - Precision Combustion
 - Efficient, High Power Density Hydrocarbon-Fueled Solid Oxide Stack System- Precision Combustion
 - Robust and Reversible Metal Supported Solid Oxide Cells for Lunar and Martian Applications - NexTech
 - Robust reversible protonic ceramic electrochemical cells for producing Lunar and Martian propellant and generating power - Special Power Sources, LLC
3. Alkaline (Dirty Water) Fuel Cells

 - Advanced Alkaline Reversible Cell (AARC) – pH Matter
 - Bifurcated Reversible Alkaline Cell for Energy Storage (BRACES) – pH Matter
3. Other Technologies

 - Lunar Regolith Hydrogen Reduction using a Hydrogen Plasma (CIF)
 - Extraterrestrial Metals Processing - Pioneer Astronautics
 - Helium and Hydrogen Mixed Gas Separator - Skyhaven Systems, LLC

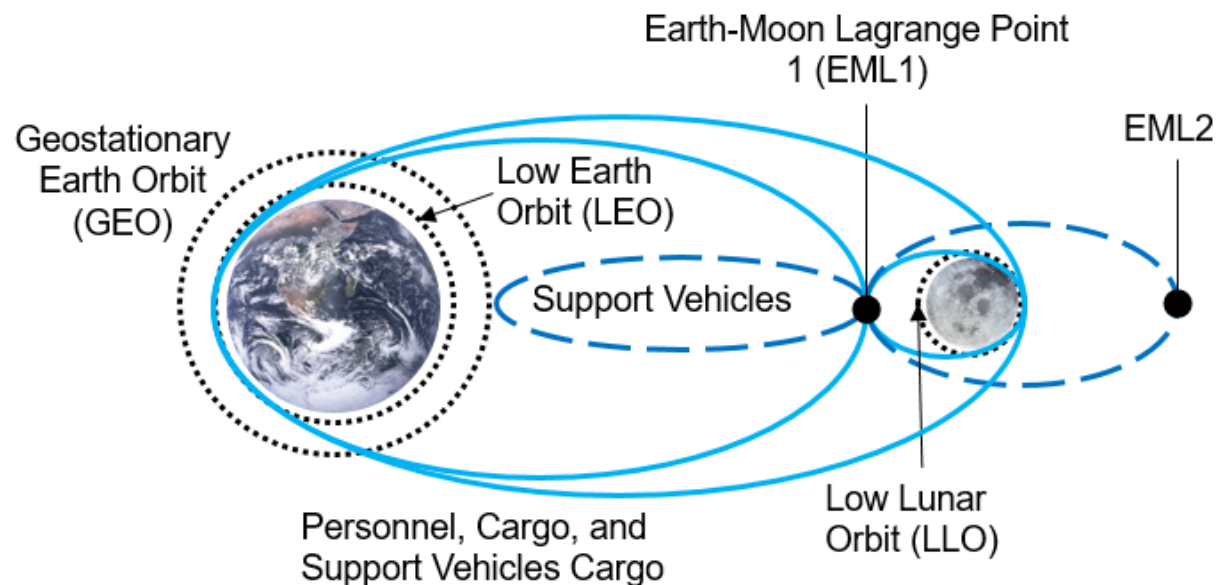
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Presentation Review



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Questions



Thank you for your attention.