National Aeronautics and Space Administration

Update on NASA Applications using Solid Oxide Fuel Cell and Electrolysis Technologies

Ian Jakupca
NASA Glenn Research Center

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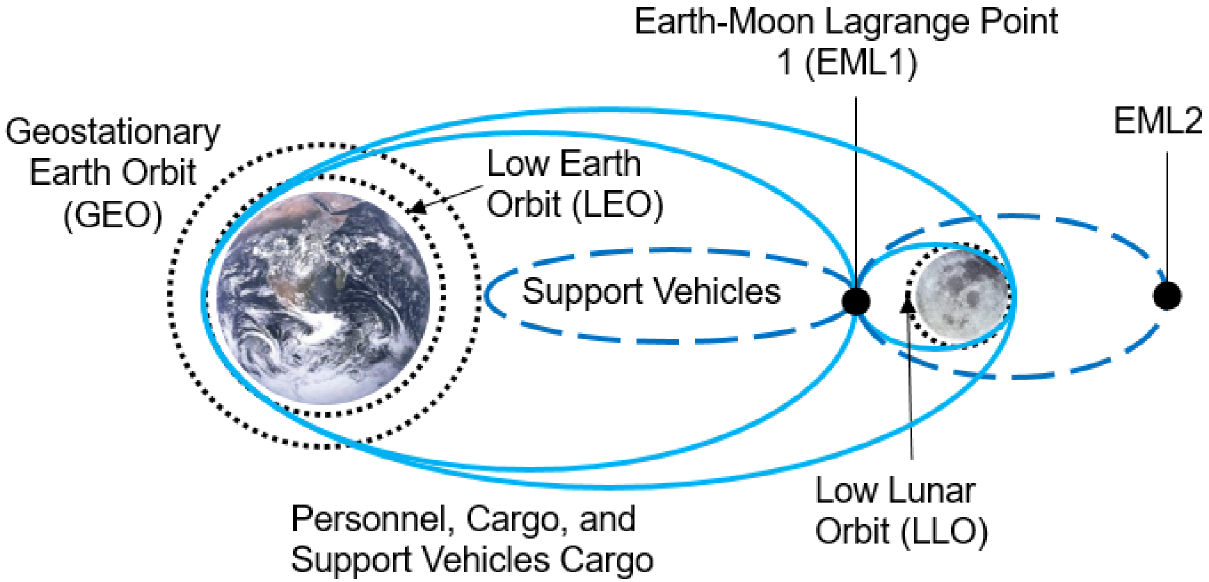
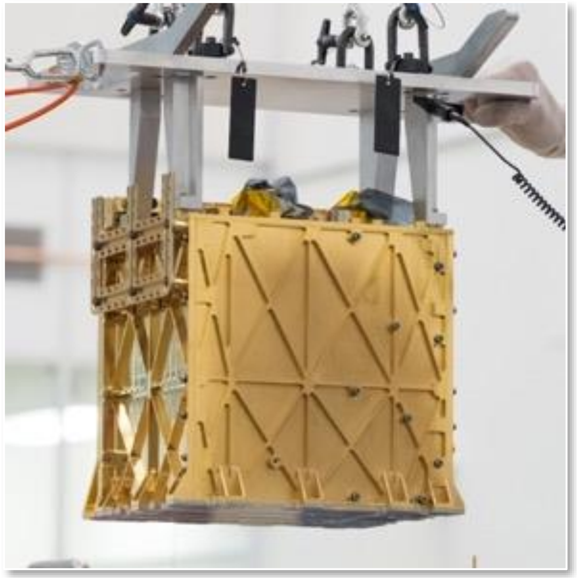
Presentation Overview

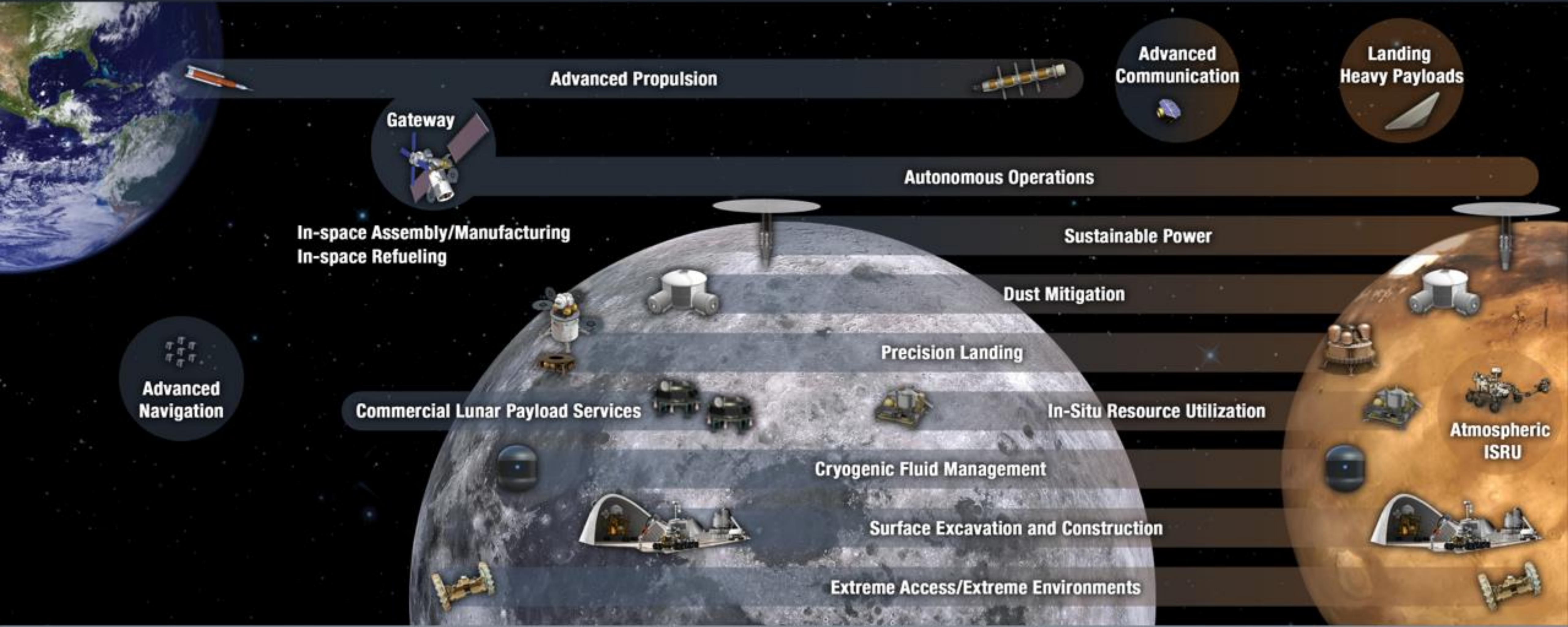
- NASA Exploration
- NASA Solid Oxide Fuel Cell and Electrolysis Applications
    - In Situ Resource Utilization (ISRU)
    - Sustainable Power
- Summary





Mars Oxygen ISRU Experiment (MOXIE)
Aboard Perseverance, demonstrated the first production of oxygen from the atmosphere of Mars Apr. 2021.

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



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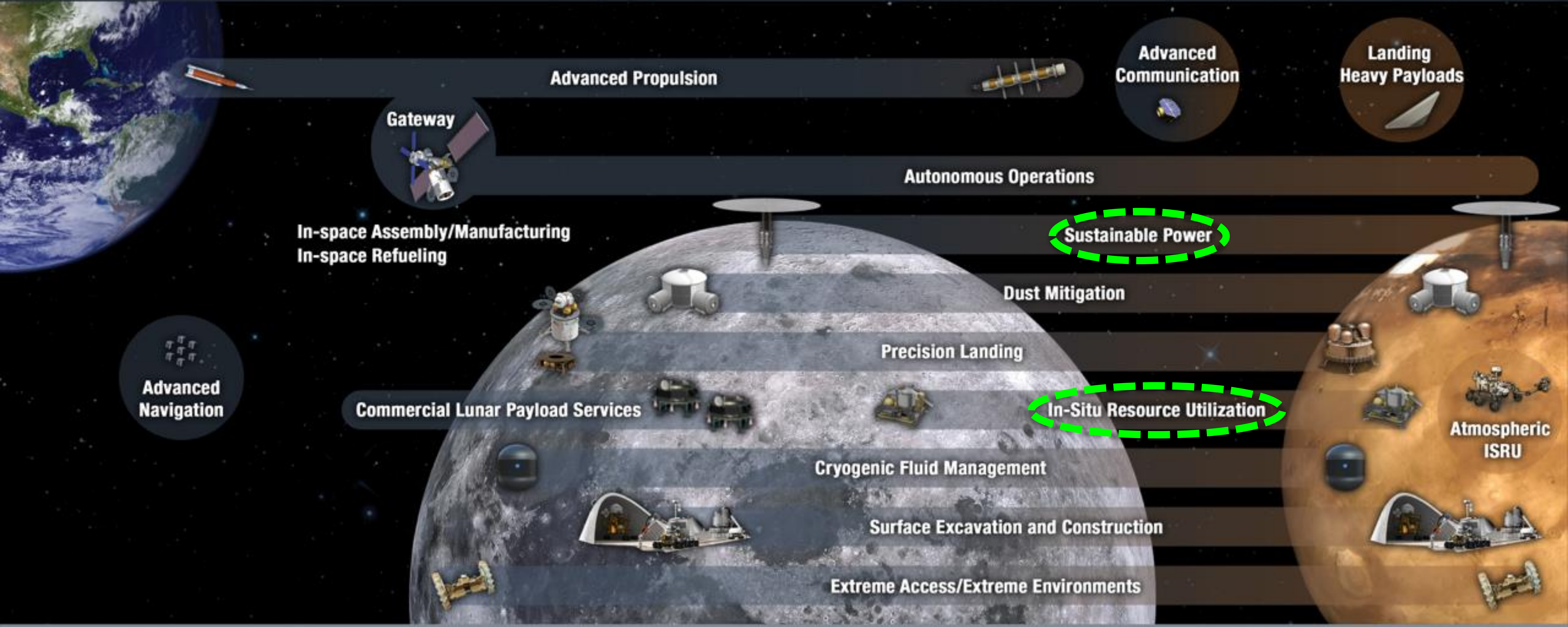


We’re going to the Moon to learn to live on other planets and for the benefit of all humanity.

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

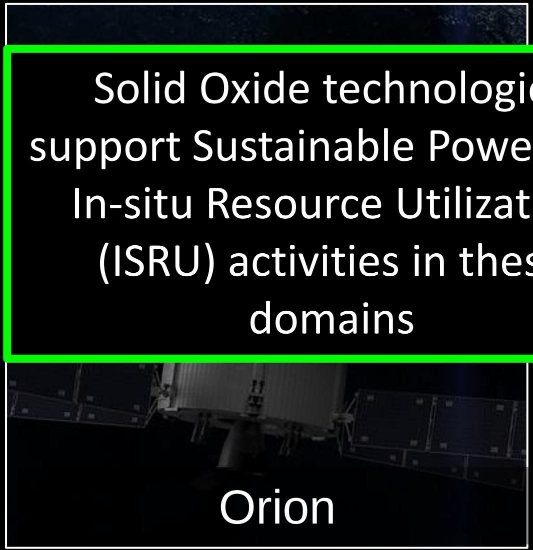
The Artemis Program Snapshot

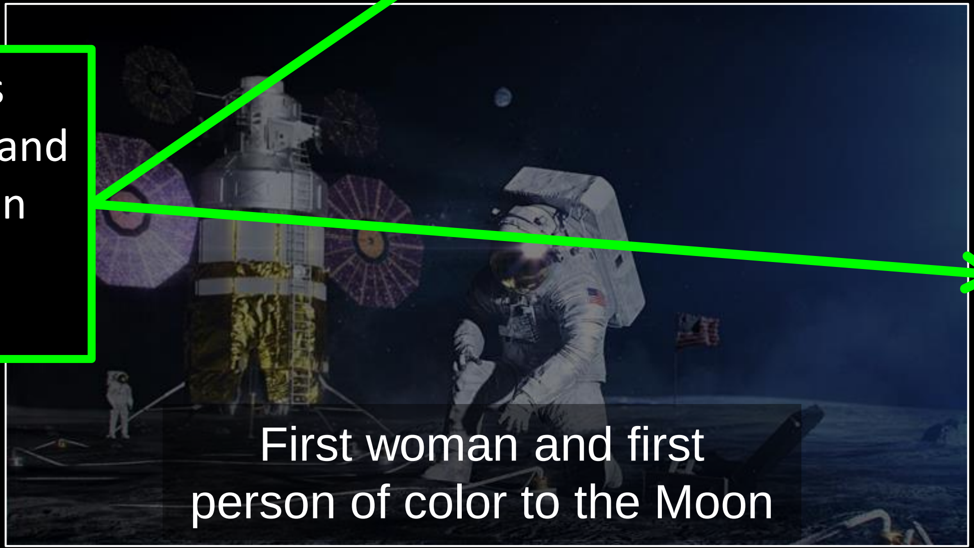

Space Launch System


Commercial Lunar Payload Services


The Gateway in lunar orbit

Solid Oxide technologies support Sustainable Power and In-situ Resource Utilization (ISRU) activities in these domains


Orion


First woman and first person of color to the Moon


Surface systems

ARTEMIS BASE CAMP

A truly sustainable infrastructure 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

EXPLORATION CAPABILITIES

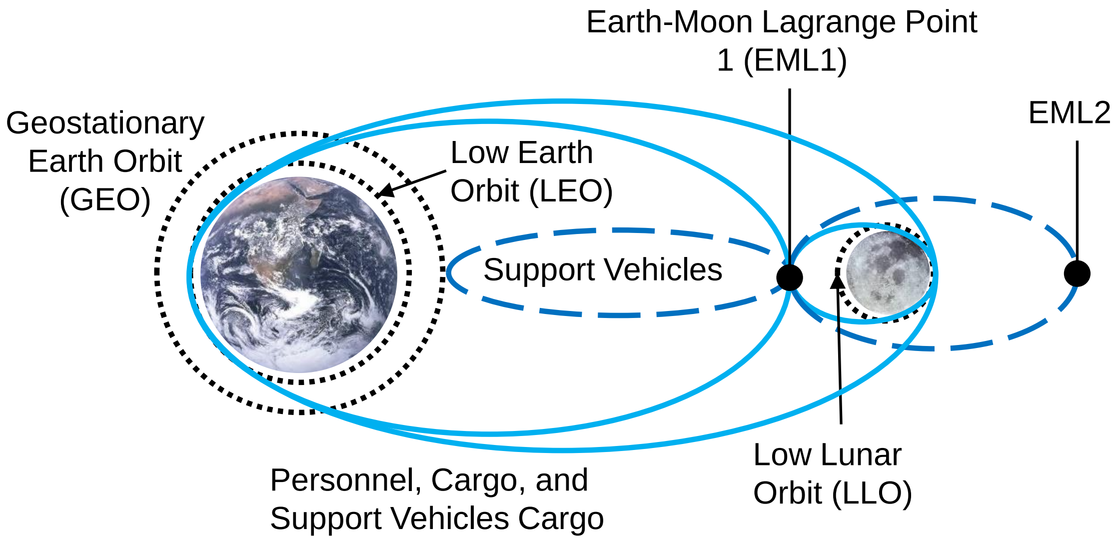
The technologies and systems that allow the crew to thrive and work in space

- Regenerative life support systems enable longer-duration missions
- Crew health and performance technology keeps astronauts safe and healthy
- New systems reduce mass, volume, and the need for resupply

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

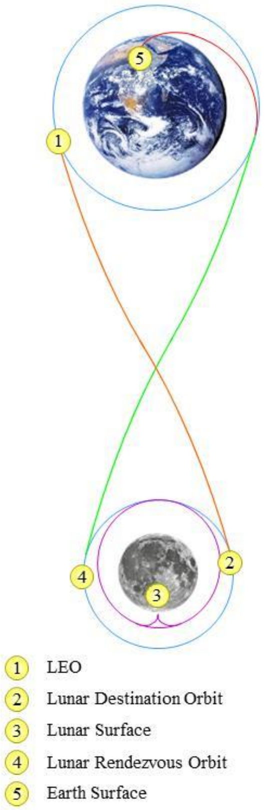


Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

- 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

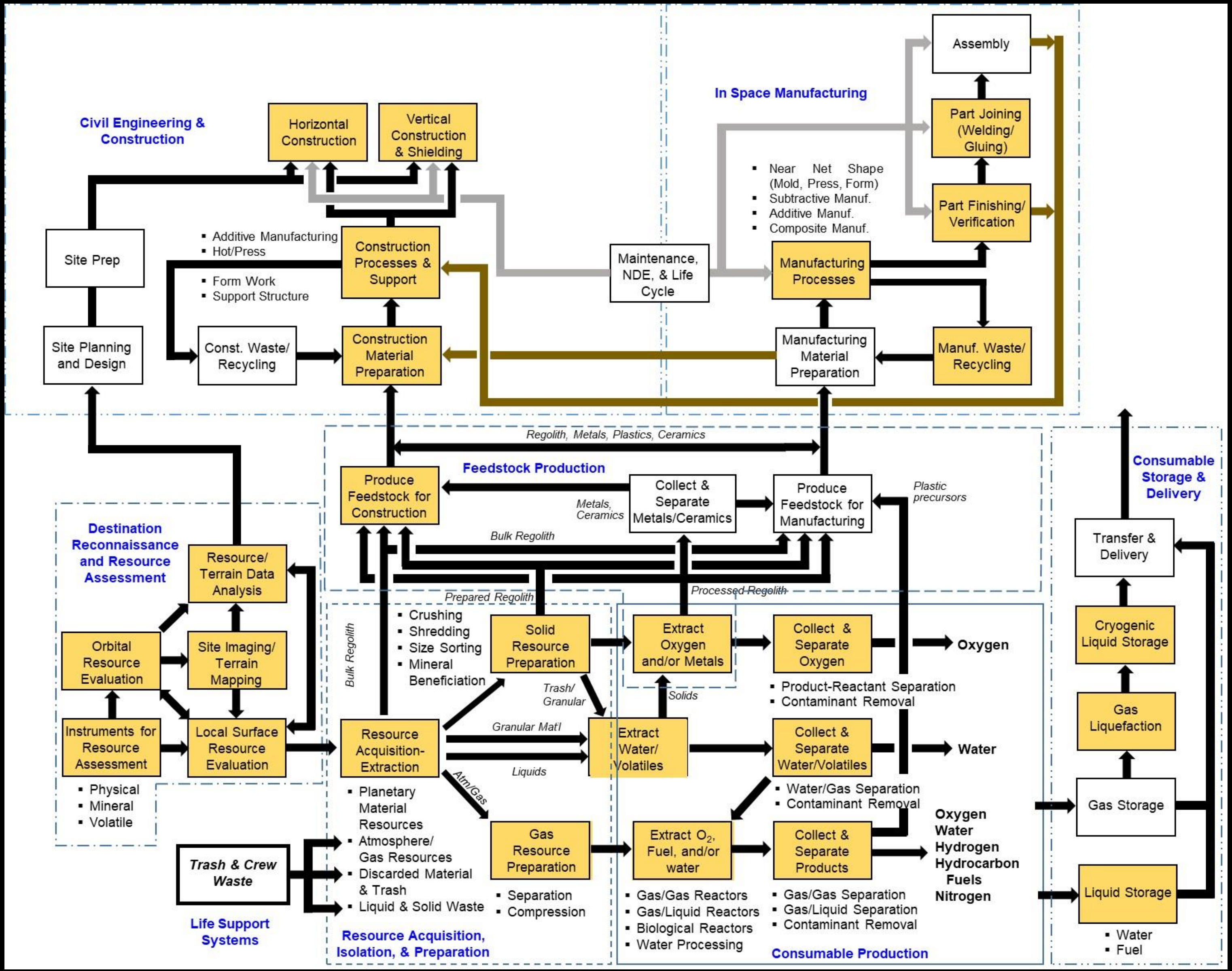
- Crew Ascent Stage (1 way): 3 to 6 mT O_2
- Single Stage (both ways): 40 to 50 mT O_2/H_2



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



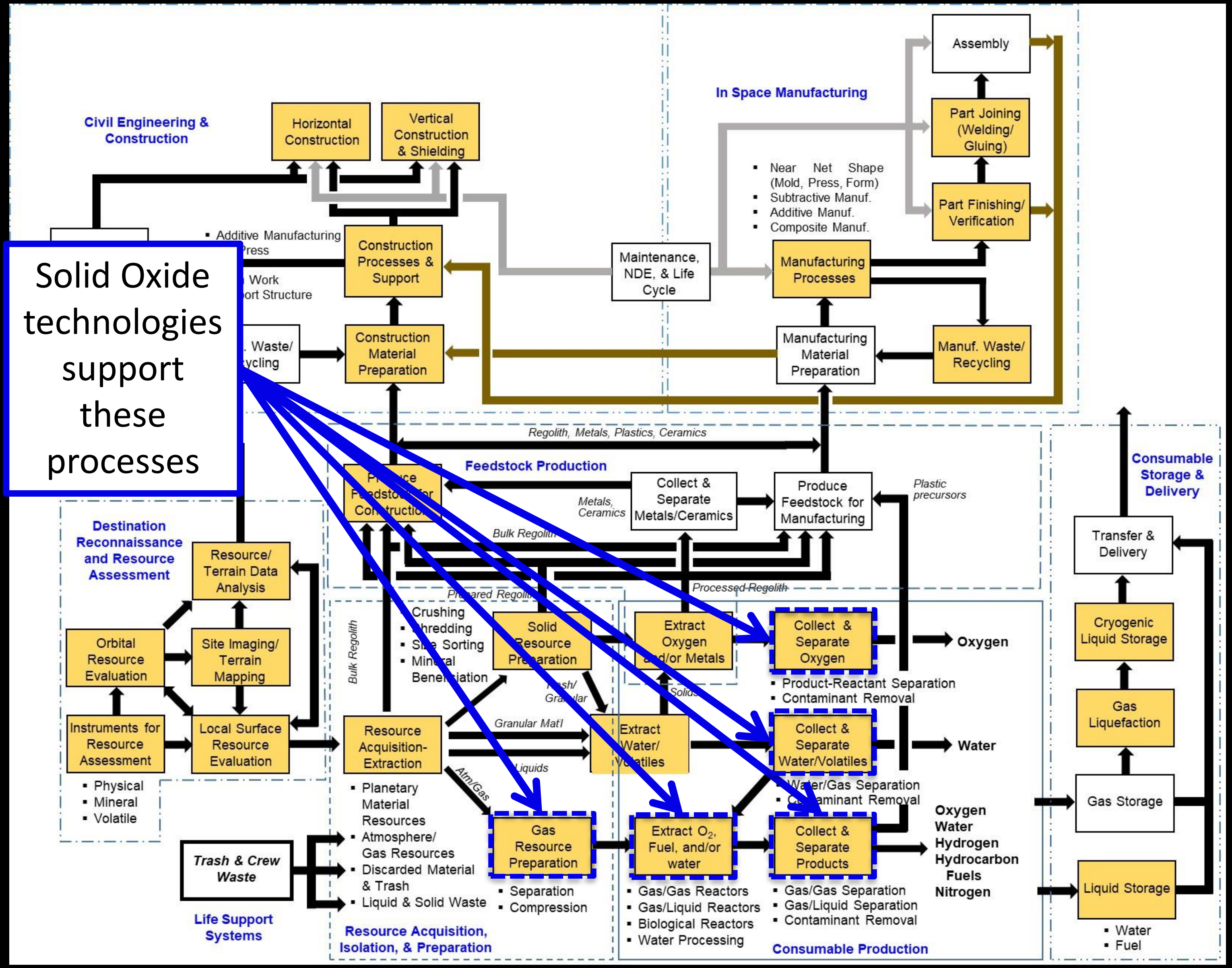
Functional Block Diagrams

- 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

= funded work

Solid Oxide Technologies Supporting ISRU on the Lunar Surface

ISRU Functional Block Diagrams



Solid Oxide Technologies can:

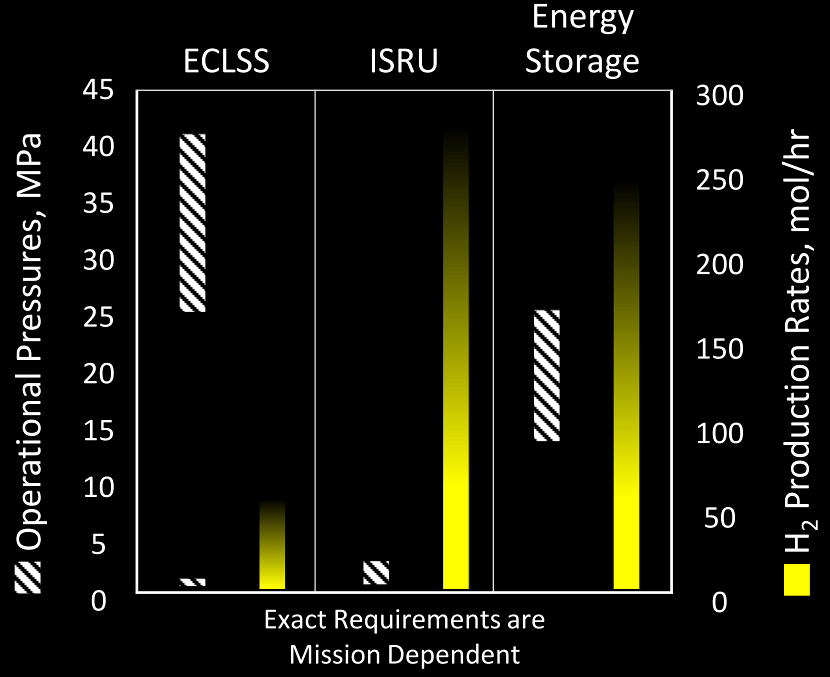
- Tolerate high contamination levels
- Integrate well with high temperature ISRU processes
- Generate H_2 and O_2
- Purify / Compress O2
- Run reversibly to provide Emergency power for limited time periods

= funded work

Solid Oxide Technologies in ISRU

Applications

- *In-situ Resource Utilization (ISRU)*
  - *Balance Design ($H_2 \approx O_2$) at low (≤ 50 psia) to medium pressures (≤ 250 psia)*
    - *Oxygen for propellants and/or Life-support applications*
    - *Hydrogen for propellants, chemical feed-stock, or metal processing*
  - *Long-term performance and reliability tolerating contaminated water sources*
  - *Process ISRU mined water containing inert and chemically active contaminants*



Technology Focus

- *Scale-up*
- *Tolerance to contaminants*
- *Metal seals*
  - *Increased pressure capability*
  - *Improved thermal cycling capability*
- *Alternative electrolytes to improve*
  - *Ionic conductivity*
  - *Thermal cycling capability*

Active Projects

- 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
- Carbothermal Reduction Reactor Design - Sierra Nevada Corp.
- Carbothermal Reactor Risk Reduction Testing and Analytical Model Development - Sierra Nevada Corp./Orbitec

Funding Sources

Internal NASA Activity	BAA
Tipping Point / ACO	SBIR / STTR

Solid Oxide Technologies in Sustainable Power

Power Generation

- *Fuel cells support DC electrical power bus*
  - *Multiple reactant types and grades (e.g. O_2/H_2 or O_2/CH_4)*
  - *Enable CLPS landers to use CH_4 propellant for Power*

- *Applications*
  - *Mars/Lunar Landers*
    - *CH_4 lowers LH_2 maintenance power during transit*
  - *Lunar/Mars surface systems*
    - *Uncrewed experiment platforms (0.1 kW to ~ 1 kW)*
    - *Crewed/uncrewed rovers (~ 2 kW to ~ 10 kW)*
    - *Crewed habitation systems (~ 10 kW modules)*

Energy Storage

- *High specific energy (W·hr/kg) means to store and release electrical and thermal energy*
  - *Lunar night: ~100 hrs (south pole) to 367 hrs (equator)*
  - *Waste heat helps systems survive the lunar thermal environment (-173°C to +105°C)*
  - *Targeting ≥ 50,000 hours maintenance interval*

- *Applications*
  - *Crewed Lunar surface systems (36 kW·hr to ≥ 1 MW·hr)*
  - *Lunar sensor network (≤ 5 kW·hr)*

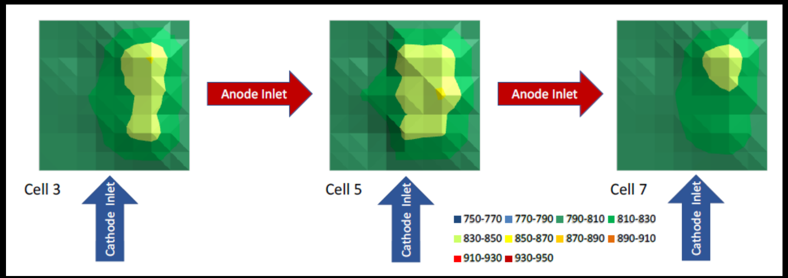
Solid Oxide Technology Focus for Sustainable Power

Power Generation

- *Scale-up*
- *Metal seals*
  - *Increased pressure capability*
  - *Improved thermal cycling capability*
- *Alternative electrolytes to improve*
  - *Ionic conductivity*
  - *Stability*
  - *Thermal cycling capability*

Energy Storage

- *Scale-up*
- *Metal seals*
  - *Increased pressure capability*
  - *Improved thermal cycling capability*
- *Alternative electrolytes to improve*
  - *Bidirectional ionic conductivity*
  - *Bidirectional stability*
  - *Thermal cycling capability*



Internal Hydrocarbon Reforming[1]

Funding Sources

Internal NASA Activity
Tipping Point / ACO
BAA
SBIR / STTR

RePCEC Solid Oxide Tube Bundle [2]

Active Projects

- Propellant Fueled Solid Oxide Fuel Cell (PropFC) - Precision Combustion
- Robust and Reversible Metal-Supported Solid Oxide Cells for Lunar & Martian Applications – NexTech and Washington St. Univ.
- Efficient, High Power Density Hydrocarbon-Fueled Solid Oxide Stack System - Precision Combustion [1]
- Highly Efficient, Durable Regenerative Solid Oxide Stack - Precision Combustion
- Reversible Protonic Ceramic Electrochemical Cells (RePCEC) – Special Power Sources[2] and Kansas State University

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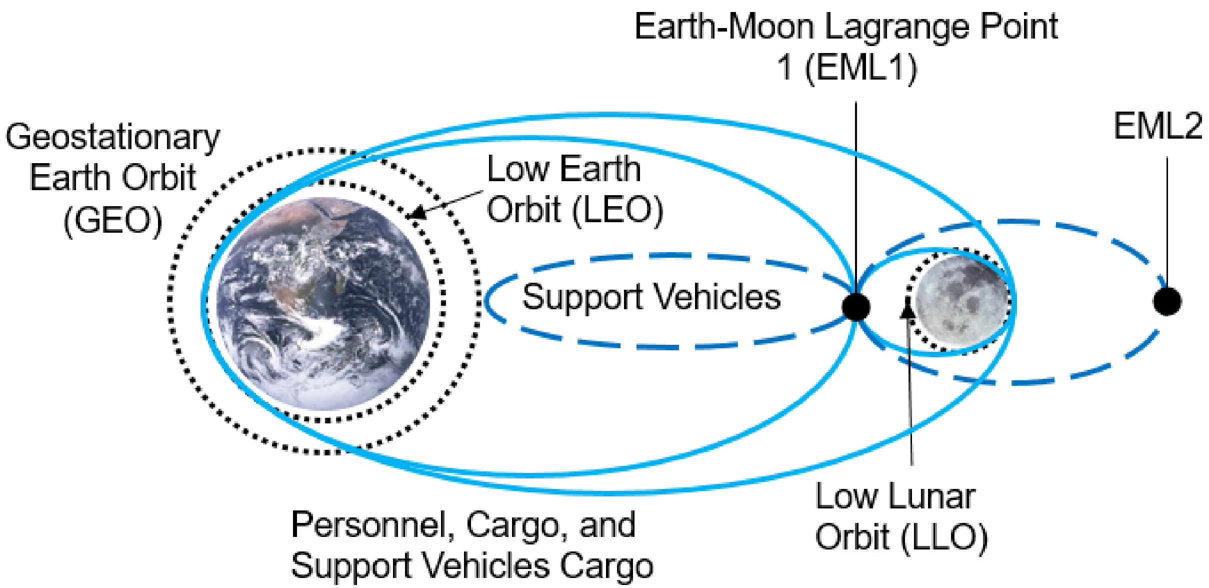

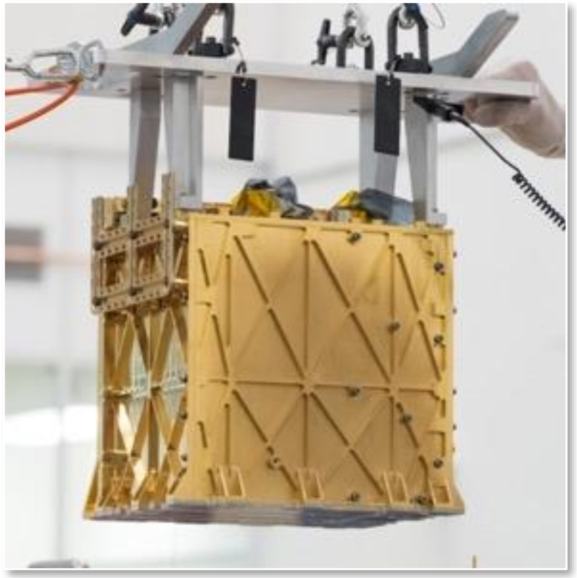

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