



Status of Primary and Regenerative Fuel Cells for Space Applications

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-



GO

LAND

LIVE

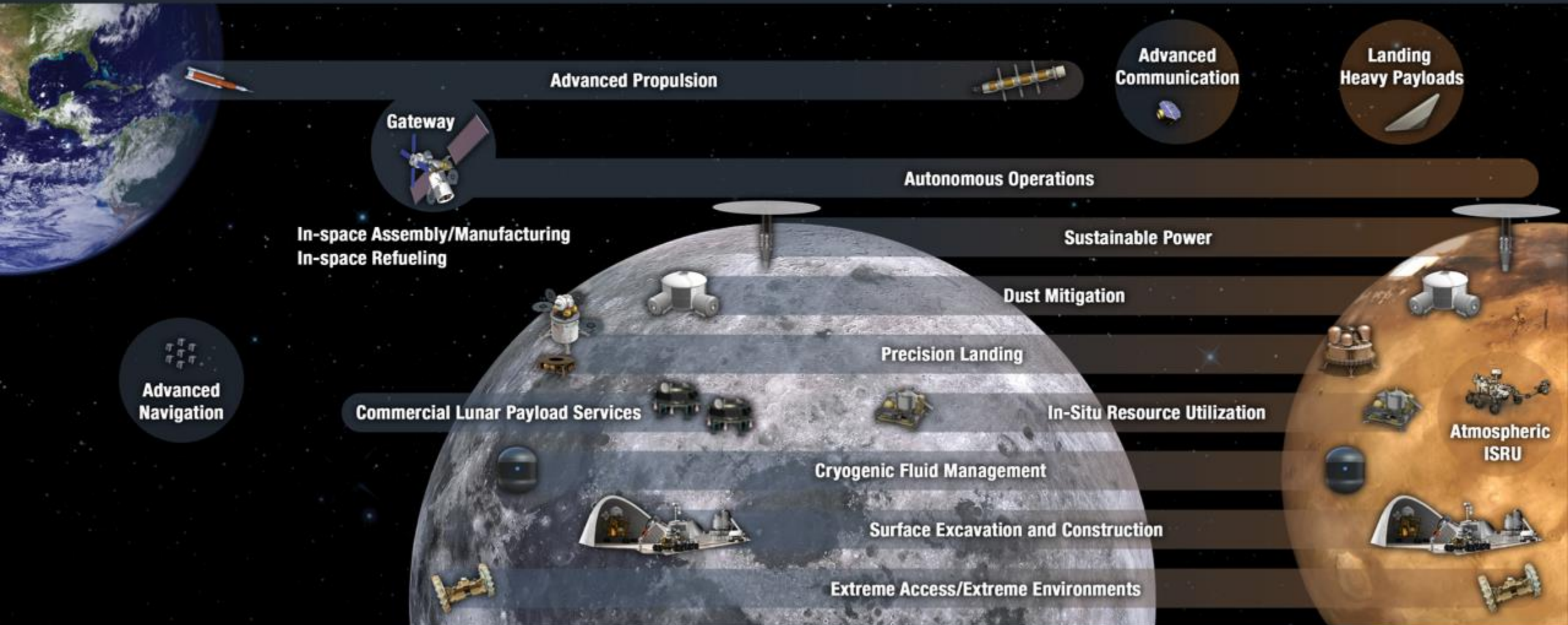
EXPLORE

Rapid, Safe, and Efficient
Space Transportation

Expanded Access to Diverse
Surface Destinations

Sustainable Living and Working
Farther from Earth

Transformative Missions
and Discoveries



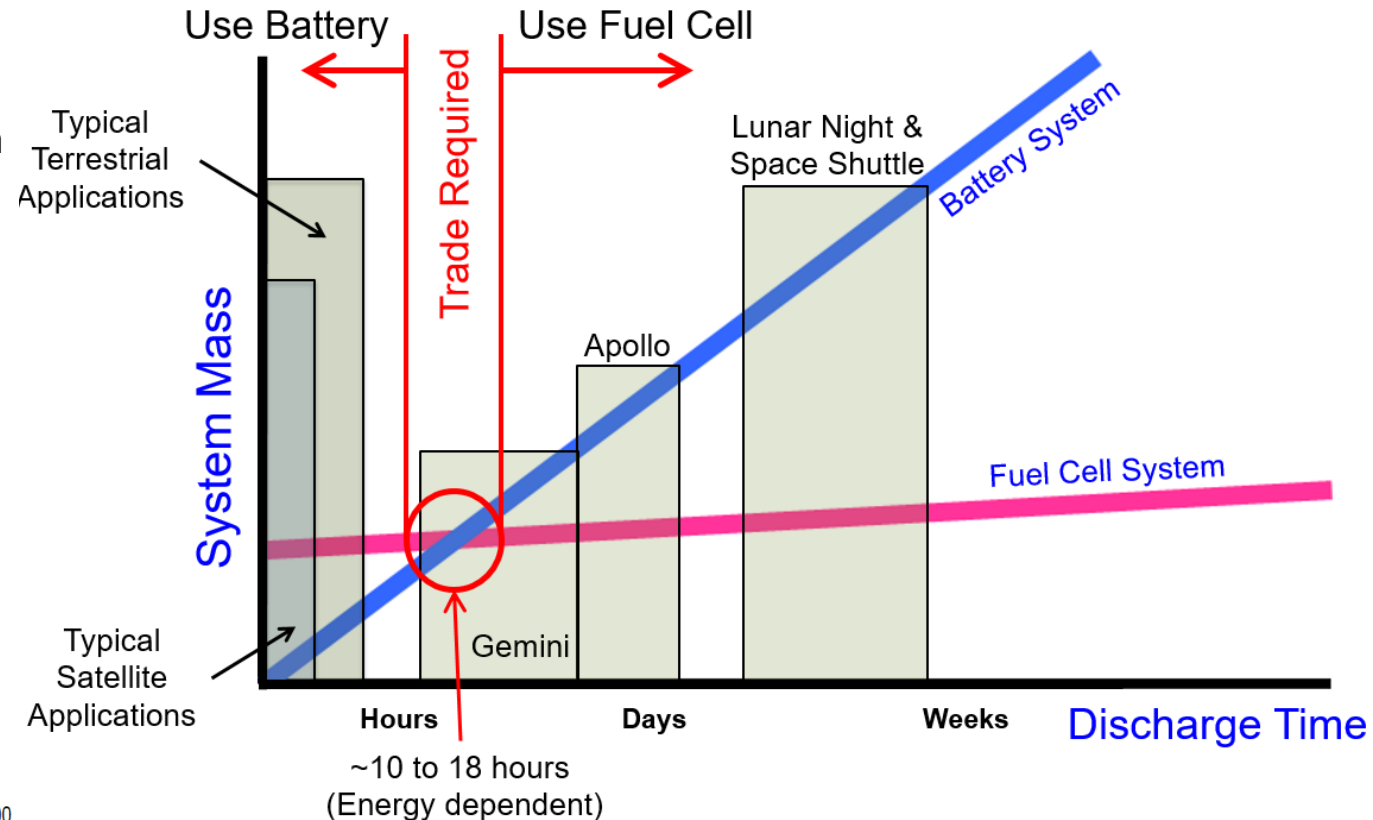
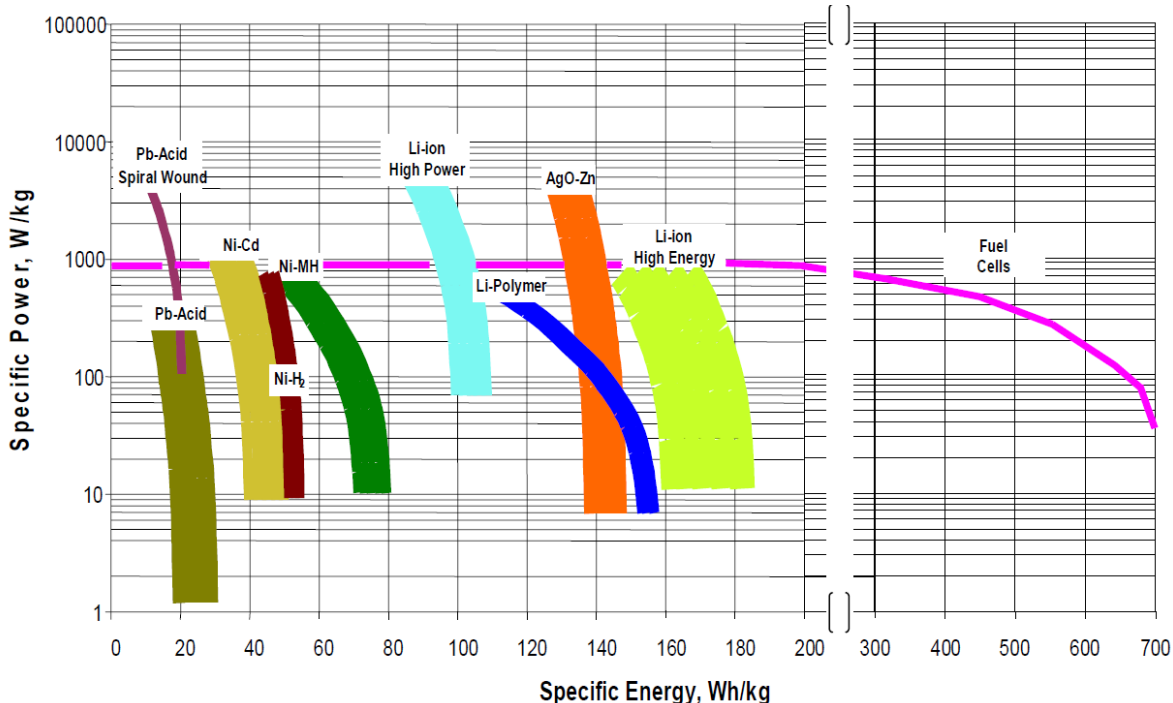
Energy Storage Options for Space Applications



- Current energy storage technologies are insufficient for NASA exploration missions
- Availability of flight-qualified fuel cells ended with the Space Shuttle Program
- Terrestrial fuel cells not directly portable to space applications
 - Different wetted material requirements (air vs. pure O_2)
 - Different internal flow characteristics
- No space-qualified high-pressure electrolyzer exists
 - ISS O_2 Generators are low pressure electrolyzers
 - Terrestrial electrolyzers have demonstrated >200 ATM operation

Energy Options for Space Applications

Battery = TRL 9
 Primary Fuel Cell = TRL 5
 Regenerative Fuel Cell = TRL 3



Electrochemistry Applicability by Lunar Mission Phase

Powering exploration activities



Launch to Trans-Lunar Injection (TLI):

Upper-Stage Launch Vehicle using propellant boil-off to extend loiter time

Cis-Lunar Transit:

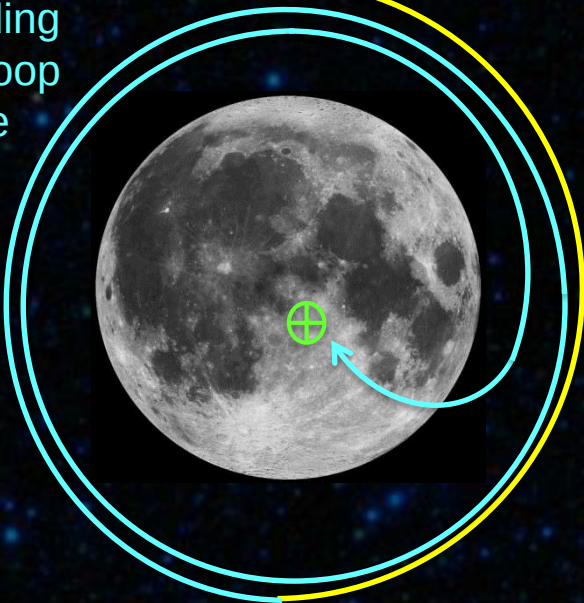
Use fuel cells only when vehicle dynamics complicate deployment of solar/PV systems

Lunar Orbit & EDL:

Power Landers in Lunar Orbit and during Entry, Descent, & Landing (EDL) to avoid bus voltage droop due to battery State of Charge

Lunar Surface:

- RFC to survive the lunar night
- Primary fuel cell to extend rover range



Mission Phase	Launch to TLI	Cis-Lunar Transit	Lunar Orbit and EDL	Lunar Surface
Overall Applicability	High	Low / Mission Specific	Mission Specific	High / Mission Specific
Primary Technical Challenge	System dynamics	μ g operation	μ g operation, System dynamics	Environment, Longevity
Applicable Technology	Fuel Cell	Fuel Cell or Electrolysis	Fuel Cell	Fuel Cell, Electrolysis, RFC
Applicable Chemistry	PEM	Mission Specific	Mission Specific	Mission Specific

POWER to explore the

LUNAR SURFACE

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



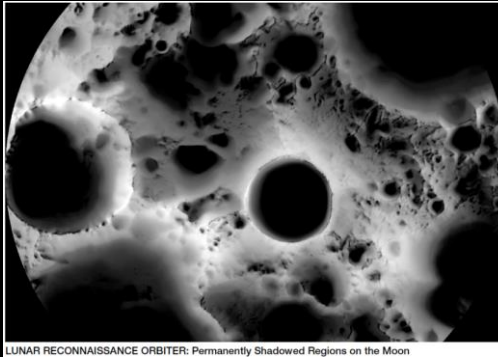
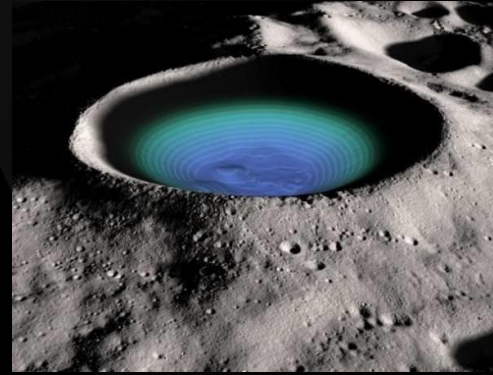
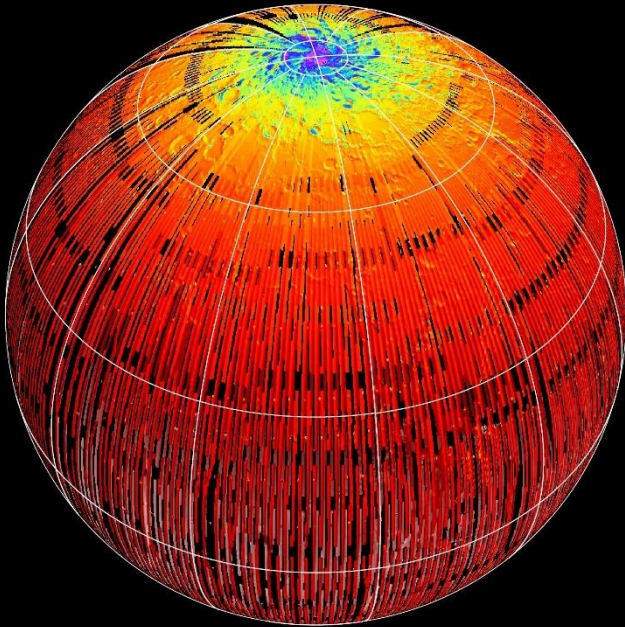
Hydrogen and Fuel Cells for Lunar Exploration

- 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

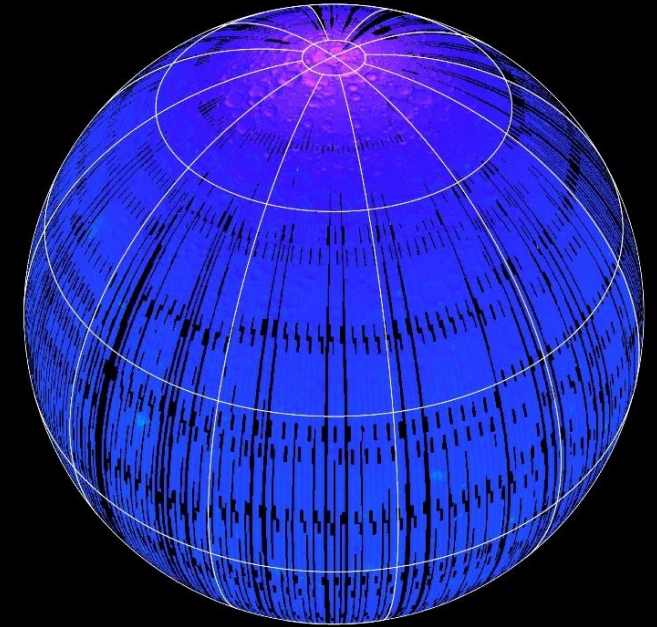
The Lunar Environment



Diviner Channel 8 Daytime Temperature (K)



Diviner Channel 8 Nighttime Temperature (K)



- 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**

Electrochemical System Definition: Primary Fuel Cells

Applicability of Terrestrial Systems to Aerospace Applications



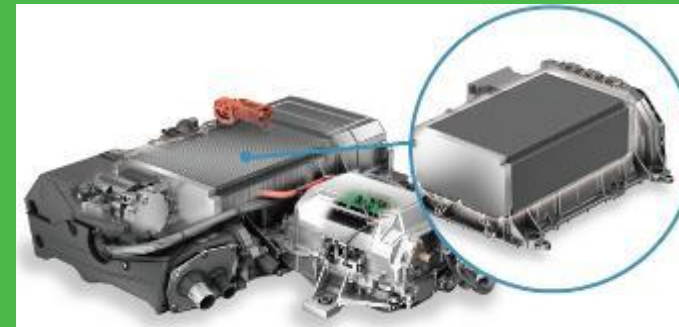
Aerospace



Space Shuttle Fuel Cell
(1979 - 2012)

≠

Terrestrial



Toyota Mirai Fuel Cell¹

Differentiating Characteristics

- Pure Oxygen (stored, stoichiometric)
- Water Separation in μg

Differentiating Characteristics

- Atmospheric Air (conditioned, excess flow)
- High air flow drives water removal

Fluid management issues and environmental conditions make aerospace and terrestrial fuel cells functionally dissimilar

Electrochemical System Definition: Primary Fuel Cells

Powering exploration activities



Discharging Only

Description

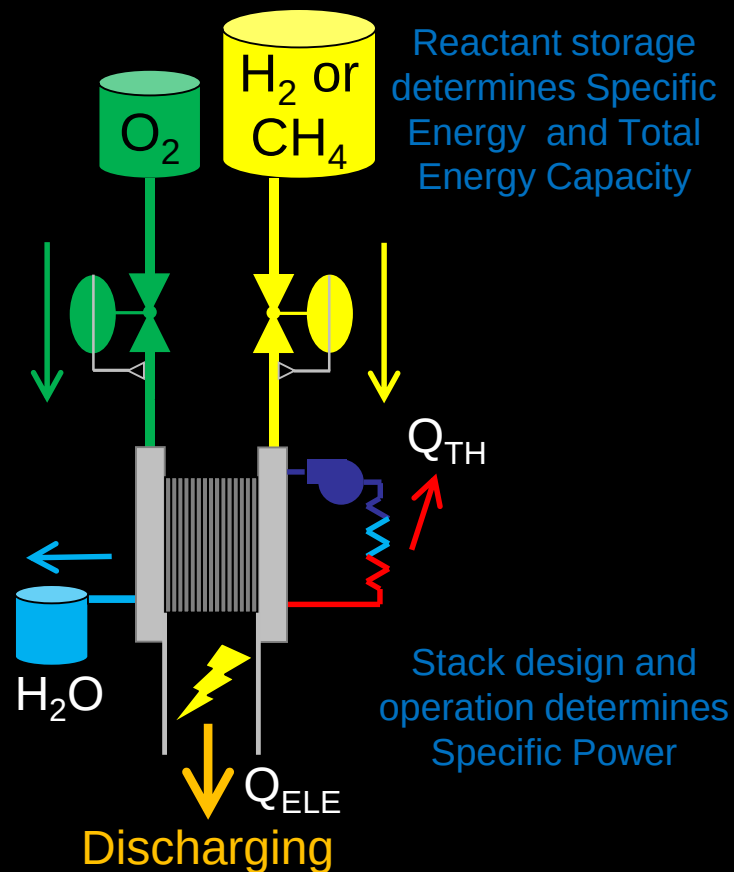
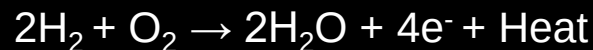
- Converts supplied reactant to DC electricity
- Operational duration limited by supplied reactants
- Not tied to external energy source

NASA Applications:

Sustained High-Power

- Upper Stage Launch Vehicles
- Crewed transit vehicles (Apollo, Gemini, STS, etc.)
- Landers
- Power-intense rovers/platforms

Example Aerospace System



Design Parameters

- Electrolyte Chemistry
 - Catalyst
 - Catalyst Support
 - Catalyst Morphology
 - Ionic Conductivity (Slew Rate)
 - Temperature Range
 - Thermal Ramp Rate
 - Water Management
- Cell Design
 - Output Current (Area of Cells)
 - Flow Field geometry
 - Materials of Construction
 - Seals
 - Thermal Control (ΔT_{Cell} , $\Delta T/\text{sec}$)
- Stack Design
 - Bus Voltage (Number of Cells)
 - Shunt Current / Corrosion
 - Seals
 - Thermal Control (ΔT_{Stack} , $\Delta T/\text{sec}$)
 - Wiring Configuration
- System Design
 - Flight Qualification
 - Reliability Data



Primary Fuel Cells: Lessons Learned

Applicability of Terrestrial Systems to Aerospace Applications

					Component	Aerospace TRL	Portability of Terrestrial Technology to Aerospace Applications	Remaining Technical Challenge
Electrolyzer Technologies	{				Electrochemistry	9	High	
					Materials	5+	High	High Pressure, Mass
					Seals	5+	High	High Pressure, Mass
					Gas Management	5+	Moderate	High Pressure, Mass
Fuel Cell Technologies	{				Flow Fields	5+	High	
					Bipolar Plates	5+	Moderate	O ₂ vs air
					Materials	5+	Moderate	O ₂ vs air
					Electrochemistry	5+	Low	O ₂ vs air, Performance
					Water Management	5+	Low	Flow Rate, μ g
Reactant Storage and Management	{				Fluidic Components	8+	Moderate	O ₂ vs air
					Procedures	5	Moderate	O ₂ vs air, Performance
					Thermal	8+	Moderate	μ g, Vacuum
					Materials	8+	Moderate	O ₂ vs air
					Water Management	5+	Low	O ₂ vs air, μ g
FC / EZ / RFC System Avionics	{				Hardware/PCB	8+	High	
					Power Management	8+	High	
					Structure	8+	High	
					Thermal	8+	High	
					Instrumentation	8+	Moderate	

NOTE:

Not all relevant technologies exist within the same application nor are at the same TRL.

Elements of multiple terrestrial applications are required to meet specific NASA mission requirements.

Primary Fuel Cells: Lessons Learned

Technology Gaps



		Catalyst				Electrolyte					Cell and Stack				System				
		Activation	Durability	Operational Life	Resilience / Recovery	Durability	Ionic Conductivity	Operational Life	Resilience / Recovery	Thermal Dynamics	Materials of Construction	Operational Life	Seals	Thermal Control (ΔT_{cell} , ΔT_{stack} , $\Delta T/\text{sec}$)	Flight Qualification	Operational Life	Reliability Data	Seals	Thermal Control (ΔT_{cell} , $\Delta T/\text{sec}$)
PEM	Launch Vehicles	A	A	A	I	A	A	A	I	A	I	A	A	A	R	A	R	A	A
	Lunar Platforms	A	A	I	I	I	A	I	I	I	I	I	A	A	R	R	U	A	R
	Crewed Outpost	A	I	I	I	I	A	I	I	I	I	I	I	A	U	U	U	A	R
Solid Oxide	Launch Vehicles	A	A	I	A	R	I	I	A	R	I	I	R	R	R	I	R	R	R
	Lunar Platforms	I	A	I	A	R	I	I	A	R	I	I	R	R	R	R	U	R	R
	Crewed Outpost	I	I	I	I	R	I	I	I	R	I	I	R	R	U	U	U	R	R

A = Acceptable

I = Improvement Beneficial / not required

R = Development / Engineering Required

U = Significant Development / Engineering

Primary Fuel Cells: Status

Powering exploration activities



Summary

- Terrestrial fuel cells have very limited portability to space applications
- Electrochemical hardware no longer the life-limiting component in a system
- No vendor offers a flight-qualified primary fuel cell system

Current Development

- Advancing Solid Oxide fuel cell technologies to generate electrical power from LOX/CH₄ propellant
 - Internal Reforming
 - New cell designs (supports, catalysts, electrolytes, etc.)
 - Stack and System designs for pure O₂ operation
- Advancing PEM stacks and systems for use in Lunar Landers
 - Environmental testing of full-sized stacks
 - Integrated fuel cell power systems
 - Supporting commercial system development

Critical PEM fuel cell technology limitations

- Adequate quantity of reliability data
- Adequate quantity of life test data
- Flight qualification

Critical Solid Oxide fuel cell technology limitations

- Inadequate seals
- Unfavorable thermal ramp rates
- Adequate reliability database
- Adequate life test data
- Flight qualification

Primary Fuel Cells: Current Projects

Powering exploration activities



Solid Oxide Fuel Cell Development

- SBIR: Internal Reforming of Propellant (CH_4)
- SBIR: High-pressure Seal Development
- Internal: Metal-supported Cell Development

PEM Fuel Cell System Development

- SBIR: Alternative Non-Flow Through Fuel Cell Technology
- Tipping Point: Procure and Test prototype PEM fuel cell systems for lunar landers

Lunar Lander Integrated Power System

- ACO: Design, build, and test prototype PEM fuel cell systems for lunar landers
- Internal: Develop detailed plan for flight certification

Funding Mechanisms

- Announcement for Collaboration Opportunity (ACO) contract
- Human Launch Systems (HSL) Appendix H call
- Small Business Innovative Research (SBIR) contracts
- Tipping Point contracts

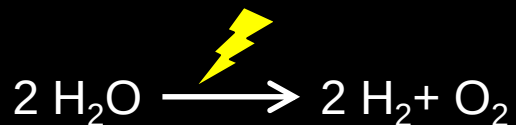


Electrochemical System Definition: Water Electrolysis

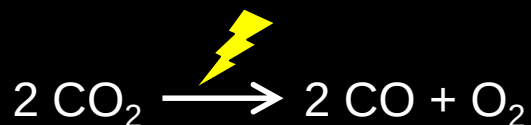


Enabling and augmenting exploration activities

Chemical Conversion



or



Description

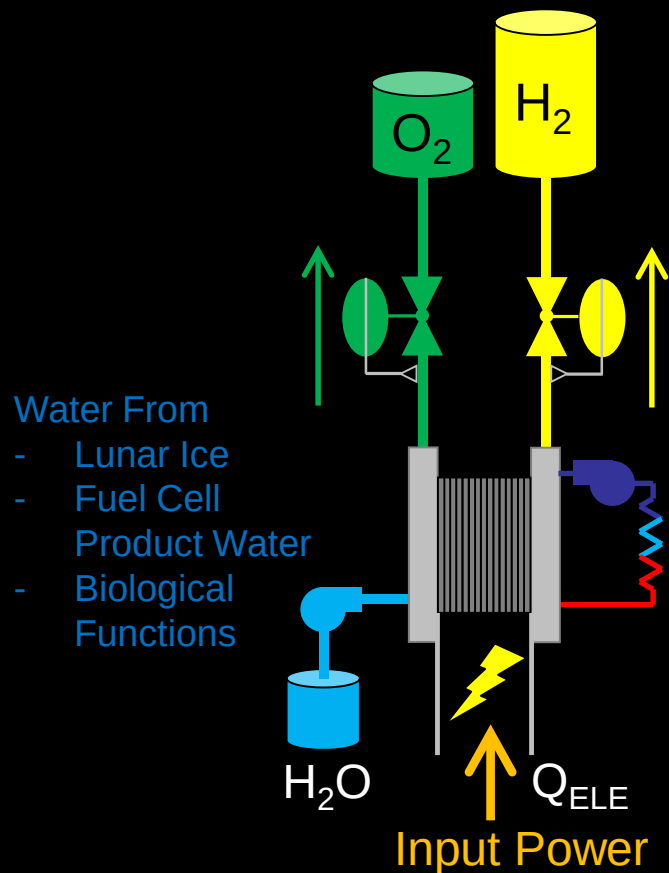
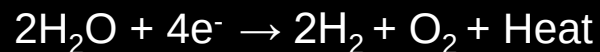
- Converts chemical feedstock into useful commodities
- Tied to external energy source

NASA Applications:

Life-support, ISRU

- Oxygen Generation
- Propellant Generation
- Material Processing

Example Aerospace System



Design Parameters

- **Electrolyte Chemistry**
 - Catalyst
 - Catalyst Support
 - Catalyst Morphology
 - Supply Slew Rate
 - Materials of Construction
 - Pressure Range
 - Reactants
 - Thermal Ramp Rate
 - Temperature Range
 - Water Management
- **Cell Design**
 - Input Current (Area of Cells)
 - Flow Field geometry
 - Materials of Construction
 - Pressure / Seals
 - Thermal Control (ΔT_{Cell} , $\Delta T/\text{sec}$)
- **Stack Design**
 - Bus Voltage (Number of Cells)
 - Shunt Current / Corrosion
 - Pressure / Seals
 - Thermal Control (ΔT_{Cell} , $\Delta T/\text{sec}$)
 - Wiring Configuration

Water Electrolysis: Lessons Learned

Technology Gaps



			Catalyst				Electrolyte				Cell and Stack				System				
			Activation	Durability	Operational Life	Resilience / Recovery	Durability	Ionic Conductivity	Operational Life	Resilience / Recovery	Thermal Dynamics	Materials of Construction	Operational Life	Seals	Thermal Control (ΔT_{Cell} , ΔT_{stack} , $\Delta T/\text{sec}$)	Flight Qualification	Operational Life	Reliability Data	Seals
PEM	ISRU	A	I	I	I	R	I	I	I	A	I	R	A	A	U	R	R	A	A
	ECLSS (Low Pressure)	A	A	I	I	A	A	I	I	A	I	I	A	A	A	I	I	A	A
	RFC (High Pressure)	A	I	I	I	R	A	R	I	A	I	R	I	A	U	U	U	A	A
Solid Oxide	ISRU	A	A	I	I	R	I	I	I	R	I	I	R	R	R	I	R	R	R
	ECLSS (Low Pressure)	I	A	I	I	R	I	I	I	R	I	I	R	R	U	R	U	R	R
	RFC (High Pressure)	I	I	I	I	U	I	U	U	U	U	U	U	R	U	U	U	U	R

A = Acceptable

I = Improvement Beneficial / not required

R = Development / Engineering Required

U = Significant Development / Engineering

Water Electrolysis: Status

Powering exploration activities



Summary

- Low-pressure PEM electrolyzers are flight qualified
- New mission needs are imposing new hardware requirements beyond current State of Art

Current Development

- ISS OGA activities working to reduce mass, increase H₂ sensor calibration stability, and other system improvements
- Developing “dirty” water electrolyzers to tolerate ISRU-generated water for generating propellants
 - Both PEM and SOFC technologies being developed
 - Typically associated with cryogenic systems
- Increasing pressure capability for ECLSS and RFC applications
 - Exclusively PEM technologies
 - Both balanced and high O₂ pressure systems for pressures >>3600 psig

Critical limitations

- Variable ISRU-water quality requirements
- Material compatibility for high pressure Oxygen
- High component mass
- Challenging environmental requirements

Water Electrolysis: Current Projects



Enabling and augmenting exploration activities

ECLSS

- Internal: OGA Mass Reduction Effort
- Internal: EVA PLSS O₂ Generation
- SBIR: High Pressure Oxygen Concentrator

ISRU

- BAA: Alkaline PEM “Dirty” Water Electrolysis
- BAA: Production of O₂ and Fuel from ISRU on Mars
- BAA: ISRU-Derived Water Purification and H₂ / O₂ Production (IHOP)
- Tipping Point: Water Processing to Propellant Generation for Liquefaction and Storage
- Tipping Point: Solid Oxide electrolysis of ISRU Water

RFC

- SBIR: Passive Water Electrolysis with Enhanced Electrode Structure

Funding Mechanisms

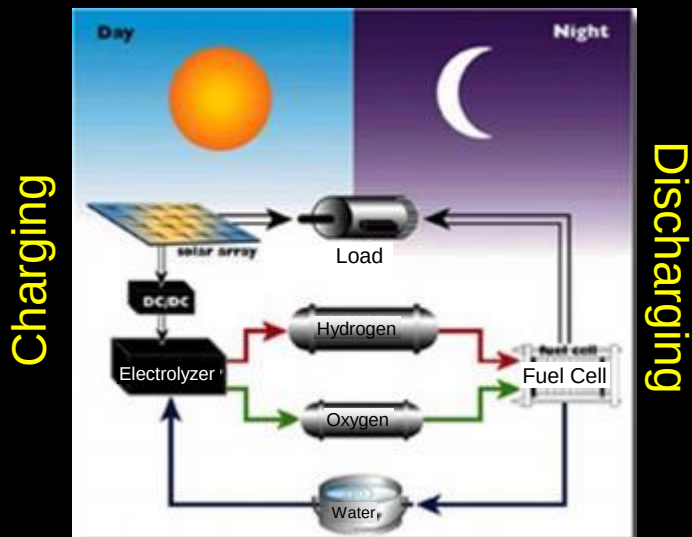
- Broad Agency Announcement (BAA)
- Internal NASA Project Funds
- Small Business Innovative Research (SBIR) contracts
- Tipping Point Contracts

Electrochemical System Definition: Regenerative Fuel Cell



Enabling and augmenting exploration activities

Charge + Store + Discharge



Description

- Stores supplied energy as gaseous reactants
- Discharges power as requested by external load
- Tied to external energy source

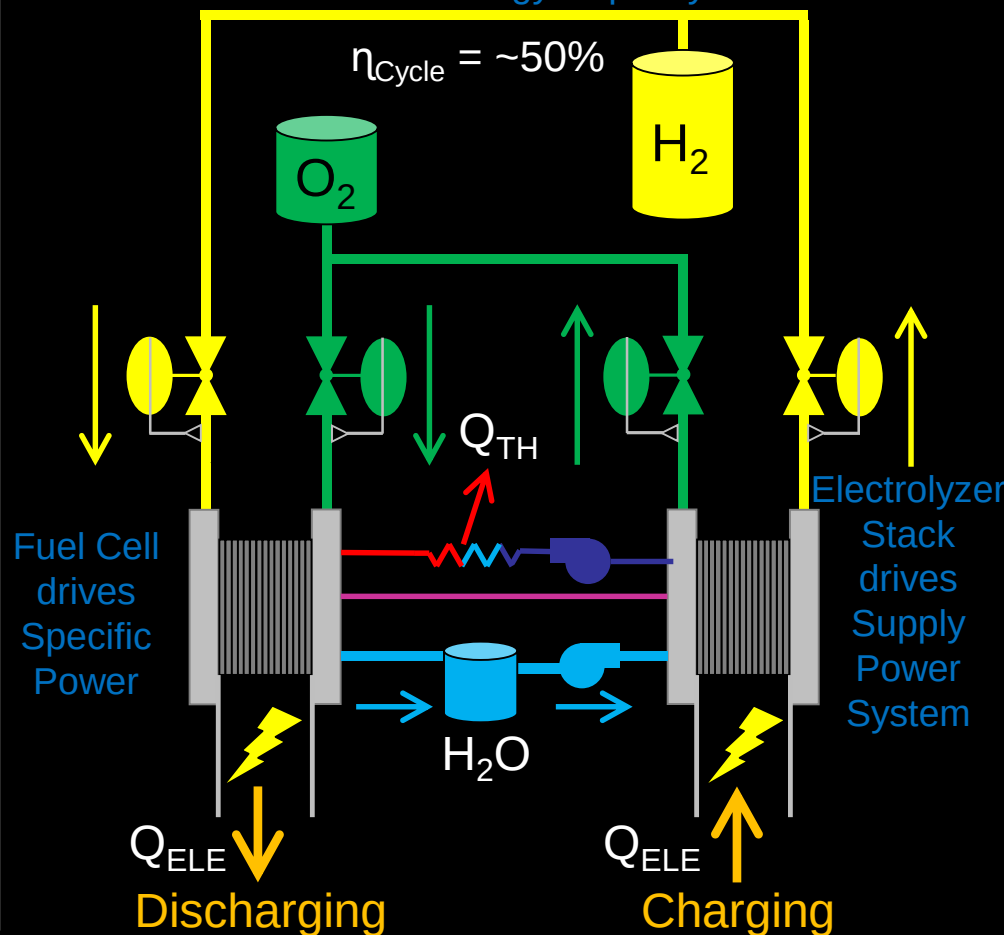
NASA Applications:

Ensuring Continuous Power

- Surface Systems (exploration platforms, ISRU, crewed)
- Platforms to survive Lunar Night

Example H_2/O_2 System

Reactant storage determines Specific Energy and Total Energy Capacity



Design Parameters

- **Electrolyte Chemistry**
 - Catalyst
 - Catalyst Support
 - Catalyst Morphology
 - Load Slew Rate
 - Materials of Construction
 - Pressure Range
 - Reactants
 - Thermal Ramp Rate
 - Temperature Range
 - Water Management
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- **Stack Design**
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 - Shunt Current / Corrosion
 - Pressure / Seals
 - Thermal Control (ΔT_{Cell} , $\Delta T/sec$)
 - Wiring Configuration

Regenerative Fuel Cells: Status

Enabling and augmenting exploration activities



Summary

- Terrestrial RFCs have been periodically demonstrated but lack a commercially viable market
- No balanced, high-pressure electrolyzer exists for aerospace applications
- Aerospace regenerative fuel cells are at a low technology readiness level
- Electrochemical hardware no longer the life-limiting component in the system

Current Development

- Leveraging other work on high pressure electrolysis and fuel cell stacks
- Developing a ground-test unit to test within a simulated lunar surface environment ($\sim 10^{-6}$ Torr, -173 °C to 105 °C)
- Trade studies for alternative packaging and chemical combinations

Critical limitations

- Low starting technology maturity
- Limited number of components that meet applications specifications
- Challenging environmental requirements

Regenerative Fuel Cells: Current Projects

Enabling and augmenting exploration activities



System Development

- SBIR: Ground testing of semi-integrated commercial systems
- SBIR: Passive Water Electrolysis with Enhanced Electrode Structure
- Internal: Develop and ground-test a RFC within a Thermal-Vacuum chamber simulating the Lunar Environment (Funded by STMD Game Changing Development Program)

Funding Mechanisms

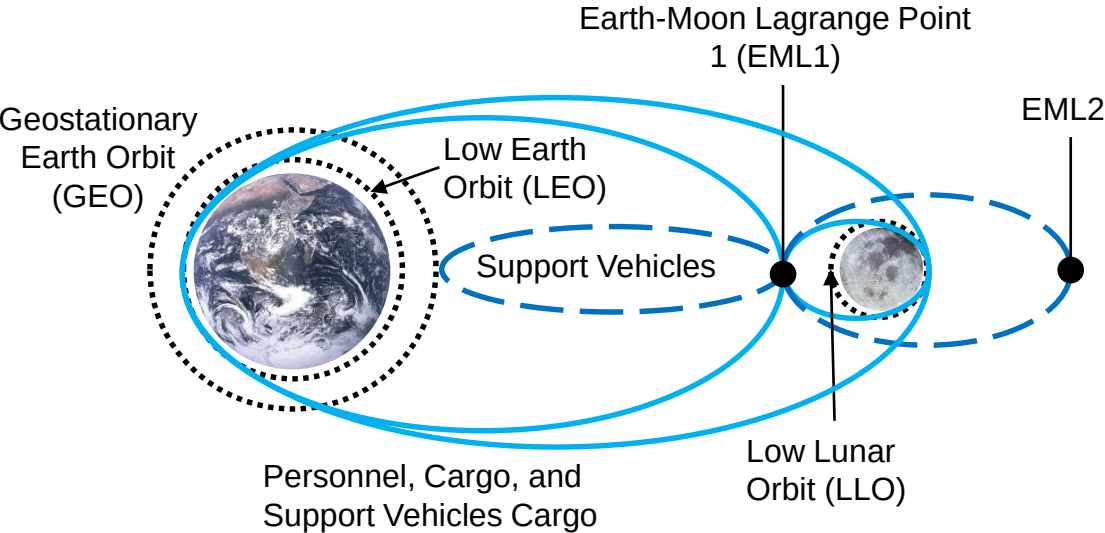
- Broad Agency Announcement (BAA)
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How Making Propellants on Planetary Surfaces Saves on Launches and Cost (Gear Ratio Effect)



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 H₂ and O₂), and consumable storage

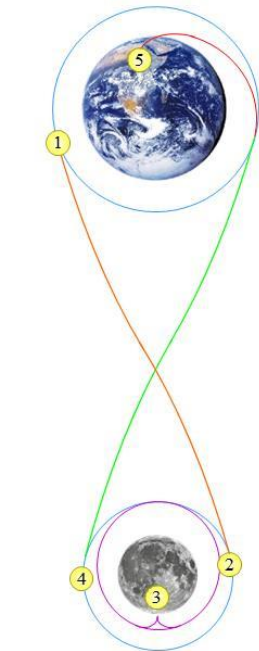


Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

- 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 O₂
- Single Stage (both ways): 40 to 50 mT O₂/H₂



- 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

Lunar ISRU Mission Consumables:

Polar Water and Oxygen from Regolith



■ Water (and Volatiles) from Polar Regolith

- Provides 100% of chemical propulsion propellant mass; Enables long-term sustainability
- Strongly influences location for sustained surface operations
- Gaps:
 - Form, concentration, and distribution of Water in permanently shadowed regions (PSRs) is not known
 - Technologies to locate and characterize resources
 - Feasibility of mining techniques and operations in PSRs not verified by ground environmental chamber tests

■ Oxygen from Regolith

- Provides 75 to 80% of chemical propulsion propellant mass (fuel from Earth); O₂ for EVA, rovers, Habs.
- Lunar regolith is >40% oxygen (O₂) by mass anywhere on the Moon
- Gaps:
 - Increase scale of ground demonstrated regolith processing by 1 to 3 orders to reach full scale production
 - Long-duration operation with abrasive regolith under lunar environmental conditions

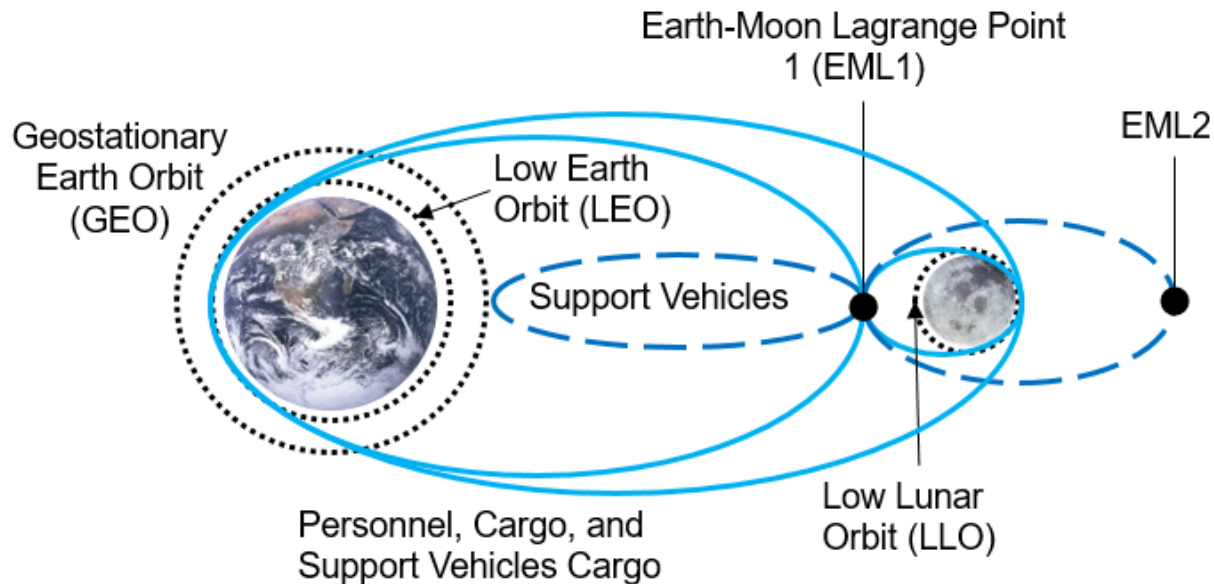
■ Current Plan: Lead with Water Mining / Follow with O₂ from Regolith Dual Path

- Perform Science/Prospecting missions to permanently shadowed regions to characterize polar water resources
- Perform ISRU technology and process risk reduction missions on CLPS landers for both paths
- Select one path (2022/23) to design pilot plant for ~2028 leading to full scale production

Presentation Summary Overview



- NASA Exploration
- Lunar Environment and Constraints
- Primary Fuel Cells for Space Applications
- Water Electrolysis in Space
- Regenerative Fuel Cell Energy Storage in Space
- *In situ* Resource Utilization (ISRU)
- Summary





Thank you for participating



Questions