National Aeronautics and Space Administration

NASA Activities in Fuel Cell and Hydrogen Technologies

Ian Jakupca
NASA Glenn Research Center

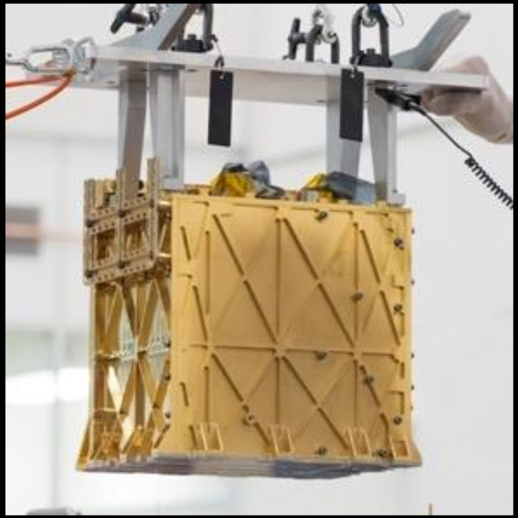
28 March 2022

Presentation Overview

- High Level Overview of fuel cell and electrolysis technologies
  - Cell, Cell Stack, Cell Stack Assembly
  - Types of Stacks
  - Types of Regenerative Fuel Cell Systems
  - Differences between Fuel Cells and Batteries

- Provide a background of NASA fuel cell and electrolysis activities technologies for Aerospace applications:
  - Reactant generation supporting Environmental Control and Life Support (ECLSS) and In Situ Resource Utilization (ISRU)
  - Reactant Transfer and Storage
  - Power and Energy Storage

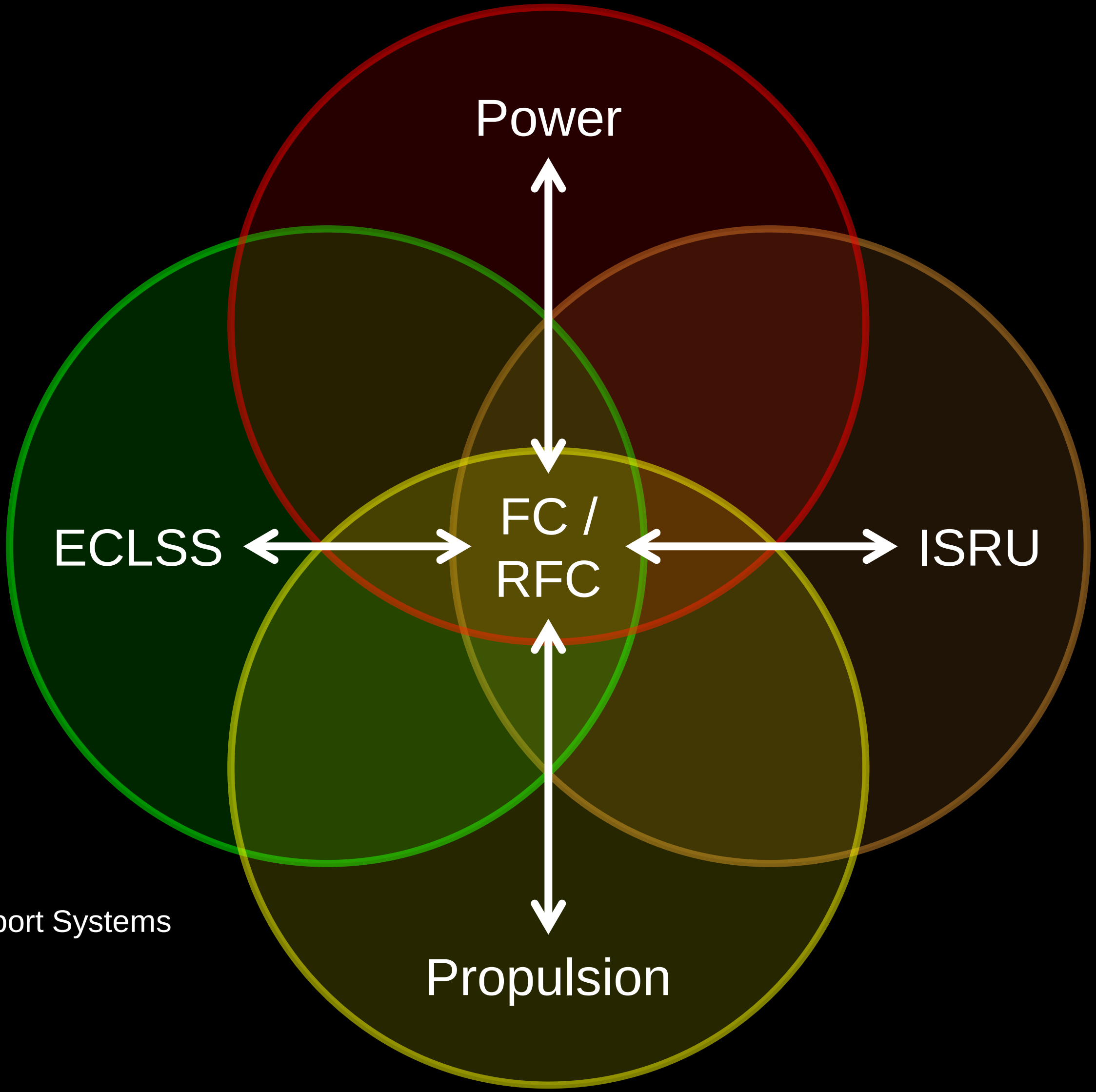
Mars Oxygen ISRU Experiment (MOXIE)
Aboard Perseverance, demonstrated the first production of oxygen from the atmosphere of Mars Apr. 2021.



Fuel Cell Powered Scarab Rover
Demonstrated field operation of H_2/O_2 fuel cell with a solar powered base of operations Aug. 2015.

Electrochemical Interoperability

With their core fuel cell and water electrolyzer technologies, multiple electrochemical applications share common reactants and power/energy requirements.



Legend
ECLSS = Environmental Control and Life Support Systems
ISRU = In Situ Resource Utilization
PMAD = Power Management and Distribution
RFC = Regenerative Fuel Cell
TRL = Technology Readiness Level
* = Application-Specific Technology Readiness Level

Aerospace Electrochemistry Options

1) Proton Exchange Membrane (PEM)
   - Low Temperature (-4 to 85 ºC)
   - Reactant Cycles
     - H_2 / O_2 / H_2O
   - TRL 5$^+$ / 9*
   - HT-PEM TRL 2*
2) Solid Oxide
   - Reactant Cycles
     - $H_2 + O_2 \leftrightarrow H_2O$
     - $(CH_4 + CO + H_2) + O_2 \rightarrow H_2O + CO_2$
   - Anionic Conducting (O^{2-})
   - Fuel cell mode TRL 3$^+$ (TRL 9 terrestrial)
   - Electrolysis mode TRL 9*
   - Protonic Conducting (H^+) TRL 3
3) Alkaline
   - Reactant Cycles
     - $H_2 + O_2 \leftrightarrow H_2O$
   - TRL 3$^+$ (TRL 9 terrestrial)

Electrochemical Systems for Space

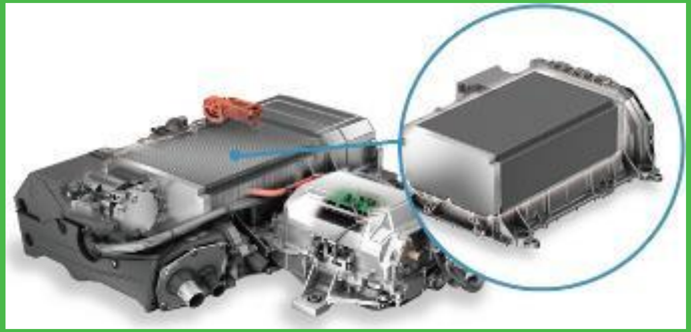
Aerospace

Space Shuttle Fuel Cell

(1979 - 2012)

≠

Terrestrial



Toyota Mirai Fuel Cell[1]

<u>Differentiating Characteristics</u>

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

<u>Differentiating Characteristics</u>

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

Fluid management issues and environmental conditions make aerospace and terrestrial electrochemical systems functionally dissimilar

Notes: [1] = http://www.toyota-global.com/innovation/environmental_technology/technology_file/fuel_cell_hybrid/fcstack.html

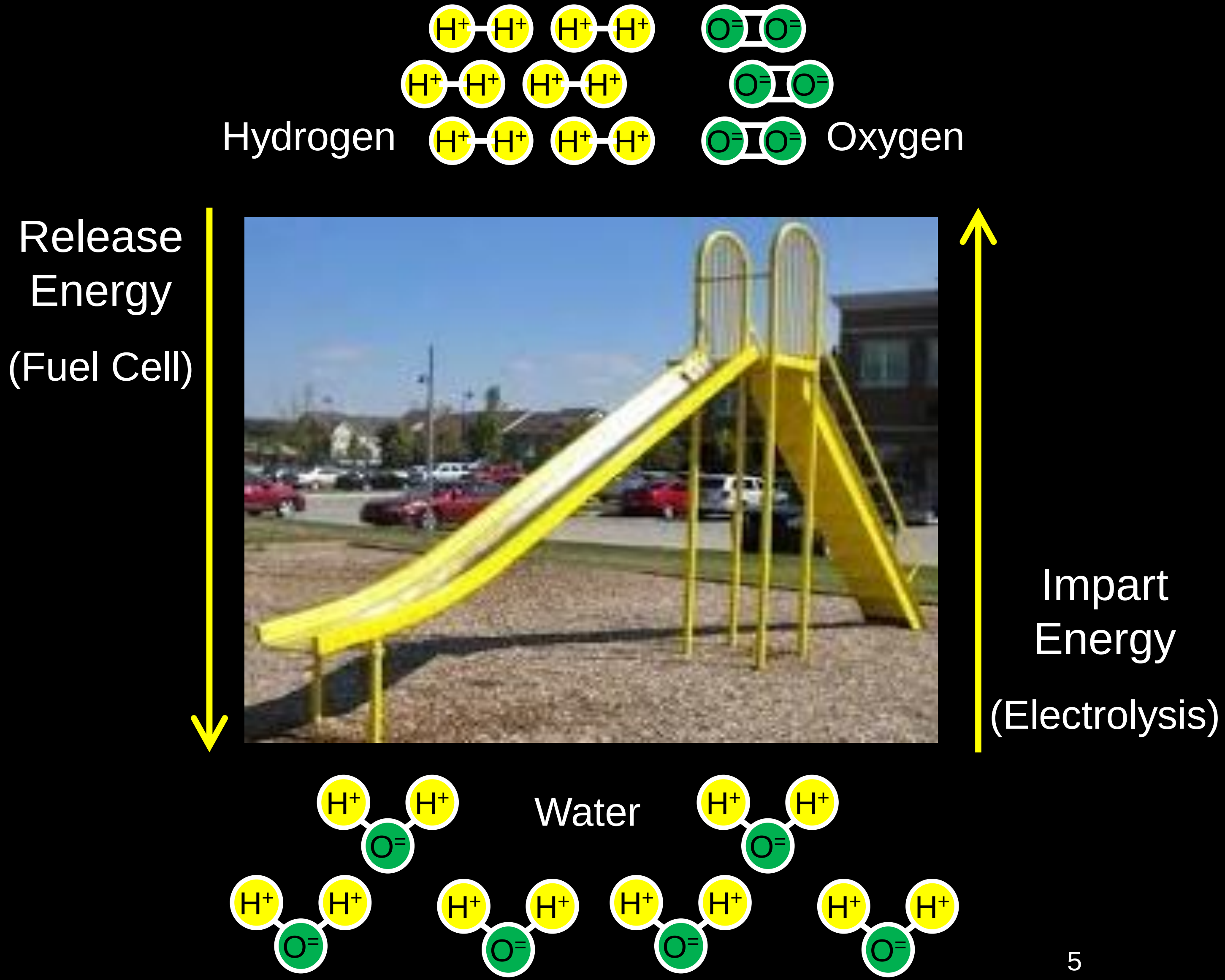
Basic Fuel Cell and Electrolysis Reactions

- NASA utilizes the reversible oxidation-reduction reactions of hydrogen, oxygen, and water for multiple applications

$$H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O$$

  - Fuel Cell reaction releases energy
  - Electrolysis reaction requires energy

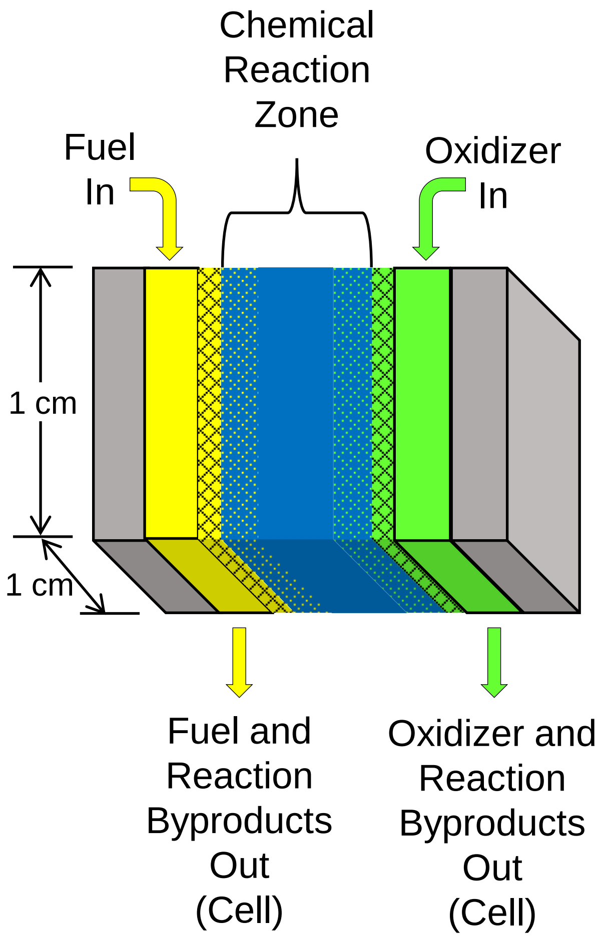
- Multiple inefficiencies limit cyclic or “round-trip” efficiency to < 60%



Basic Electrochemical Stack

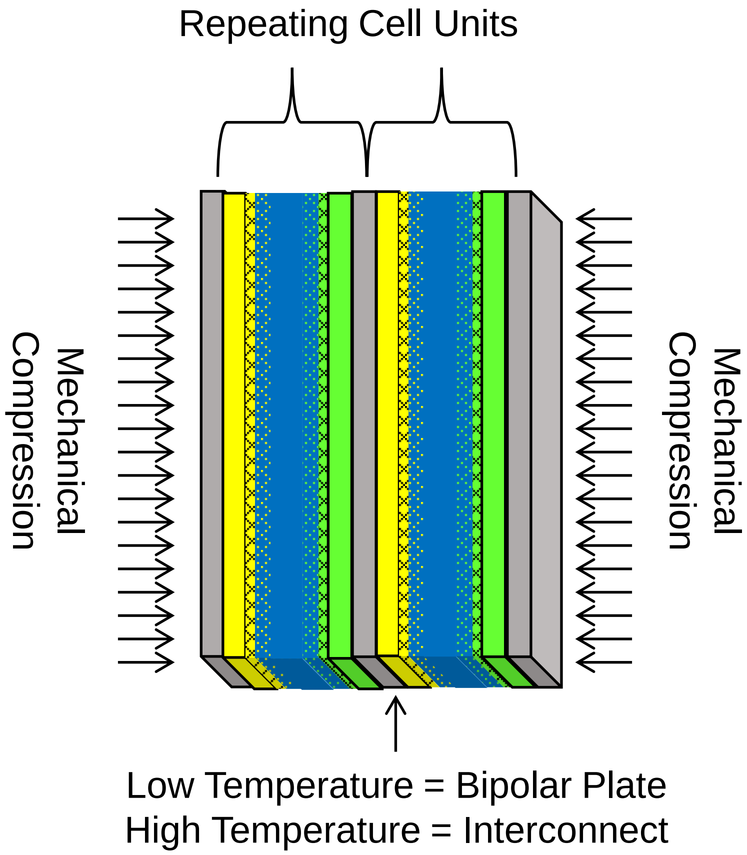
Unit Cell

Fundamental Working Unit



Cell Stack

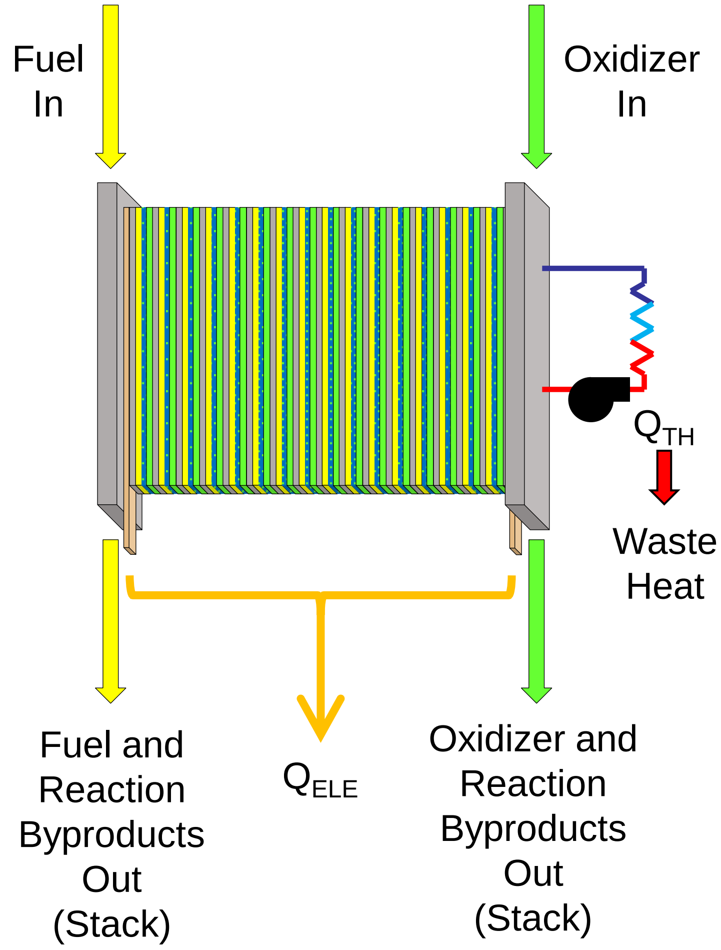
"Filter-Press" Design



Not Shown: Fluid Manifolds connecting process fluids to each cell

Cell Stack Assembly

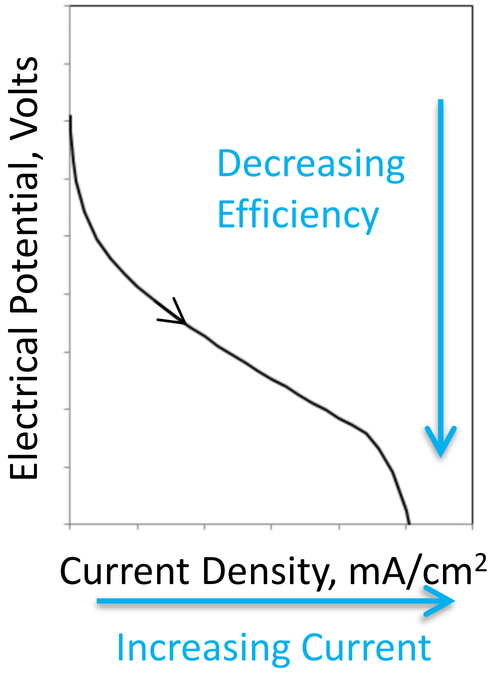
Base System Unit



Basic Electrochemical Systems

Fuel Cell Applications
- Primary power
- RFC Discharge power
- Operational duration based on reactant storage

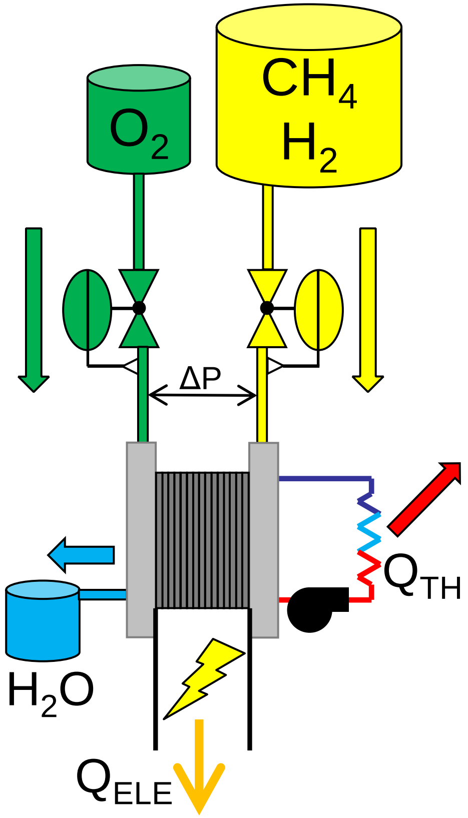
Fuel Cell Performance



Primary Fuel Cell

Discharge Power Only

$2H_2 + O_2 \rightarrow 2H_2O + 4e^- + Heat$

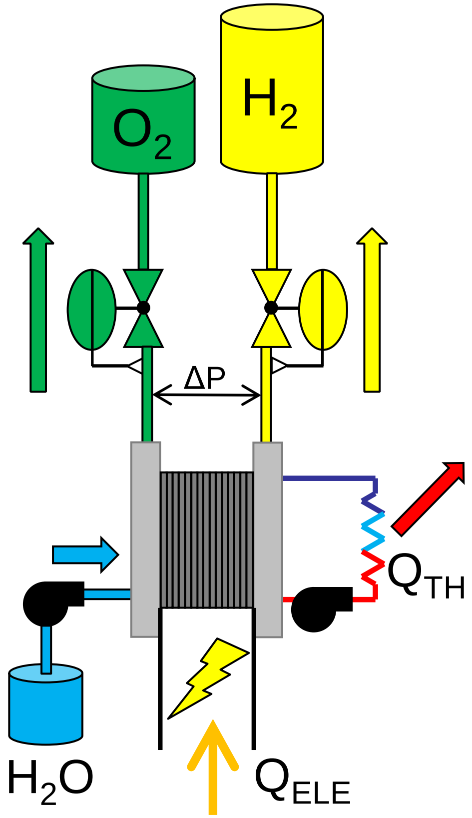


Discharging

Electrolysis

Chemical Conversion

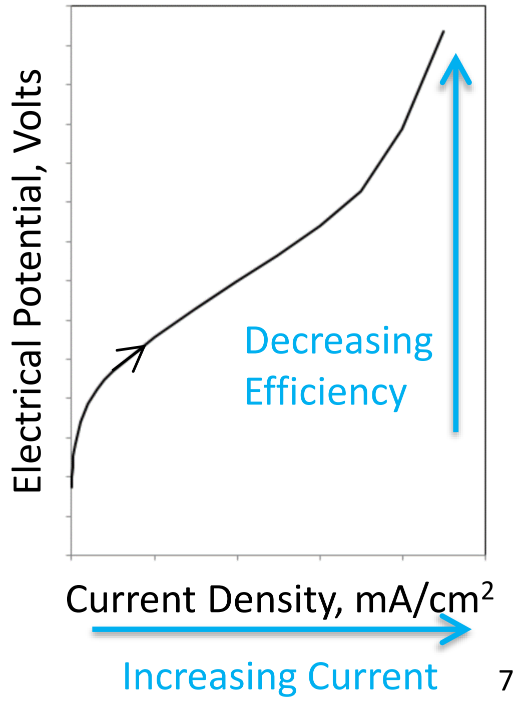
$2H_2O + 4e^- \rightarrow 2H_2 + O_2 + Heat$



Charging

Electrolysis Applications
- Life Support (O_2 Generation)
- Propellant Generation (H_2 and O_2 Generation)
- RFC Charging (H_2 and O_2 Generation)
- ISRU Material Processing

Electrolysis Cell Performance

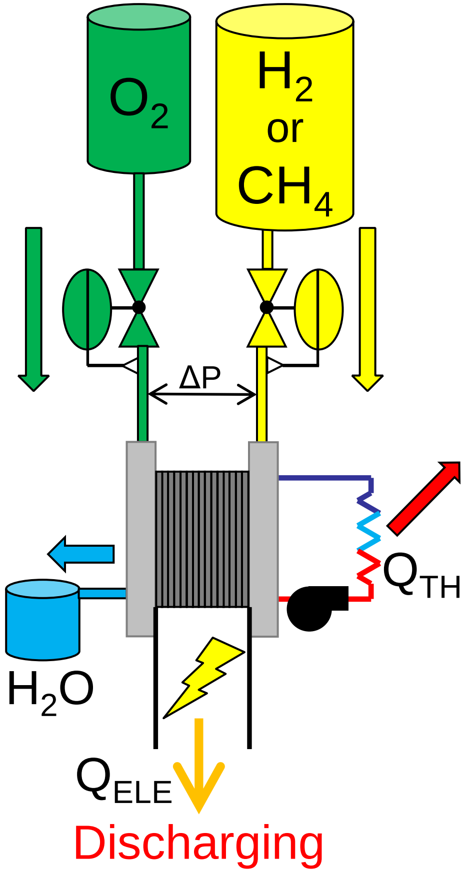


Electrochemical Systems for Space

Primary Fuel Cell

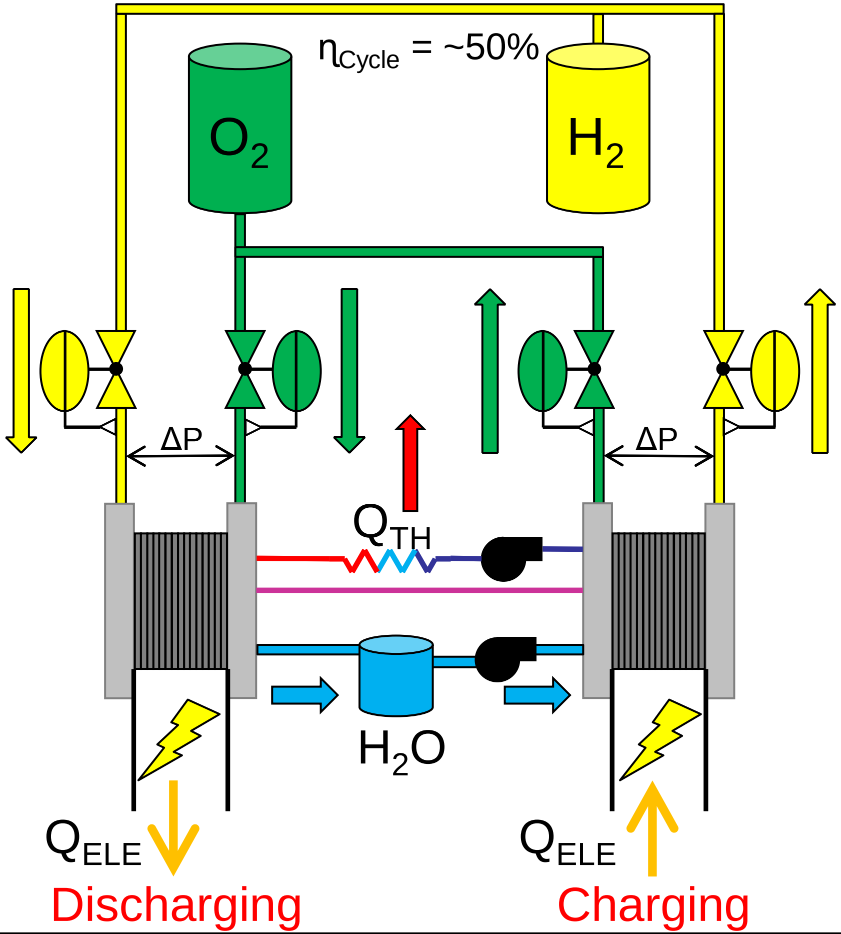
Discharge Power

$2H_2 + O_2 \rightarrow 2H_2O + 4e^- + \text{Heat}$



Regenerative Fuel Cell

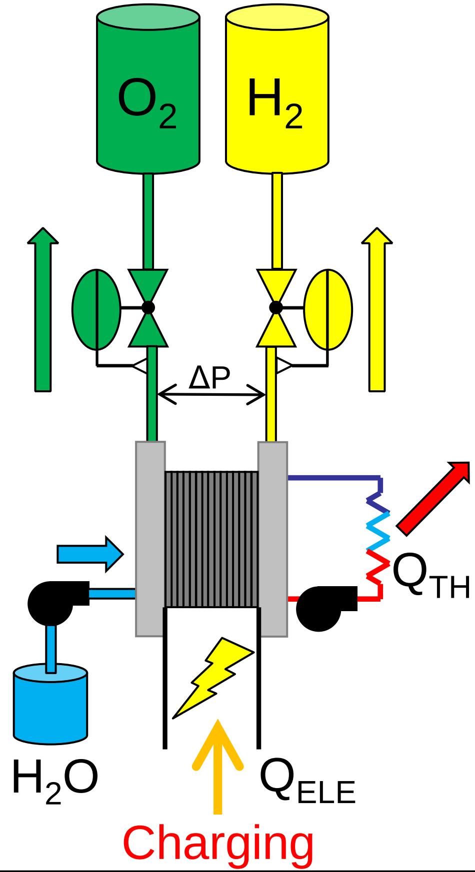
Energy Storage



Electrolysis

Product Generation

$2H_2O + 4e^- \rightarrow 2H_2 + O_2 + \text{Heat}$



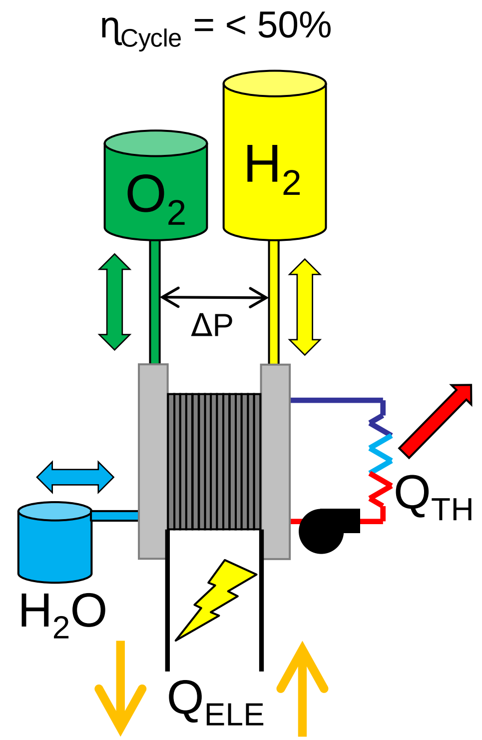
Regenerative Fuel Cell = Fuel Cell + Interconnecting Fluidic System + Electrolysis

Regenerative Fuel Cell Systems

Unitized RFC

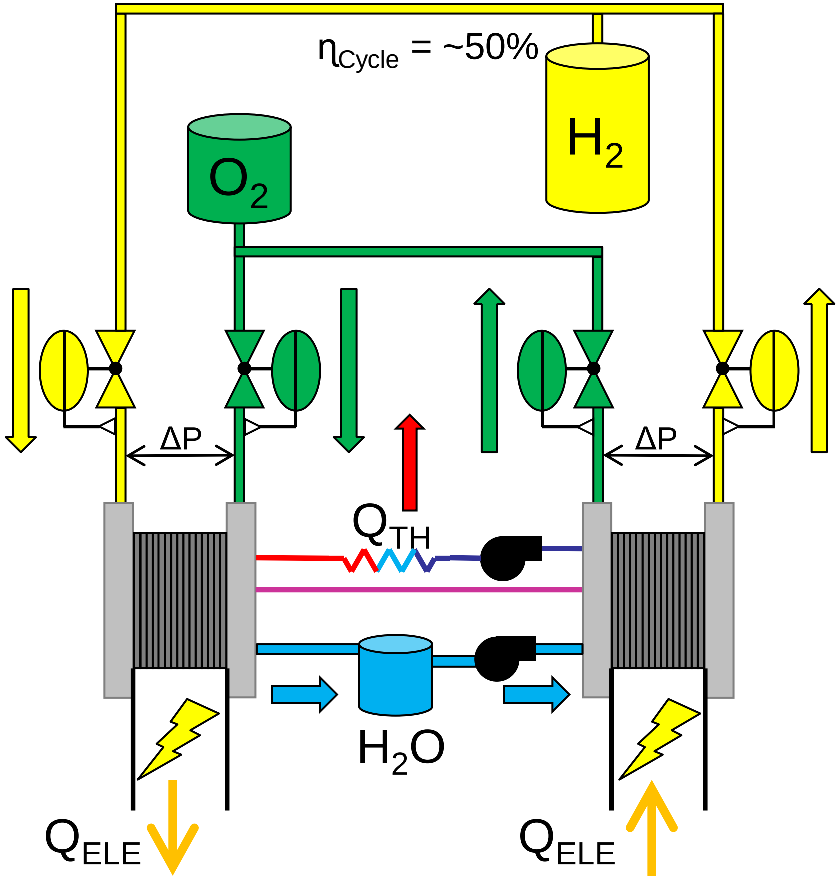
Energy Storage System

Notes
- Very low TRL for space applications
- Operational pressure limited resulting in very large tanks or independent compression
- Limited by water management issues in low temperature chemistries
- Significant recent investment indicating some promise



Discrete RFC

Energy Storage System

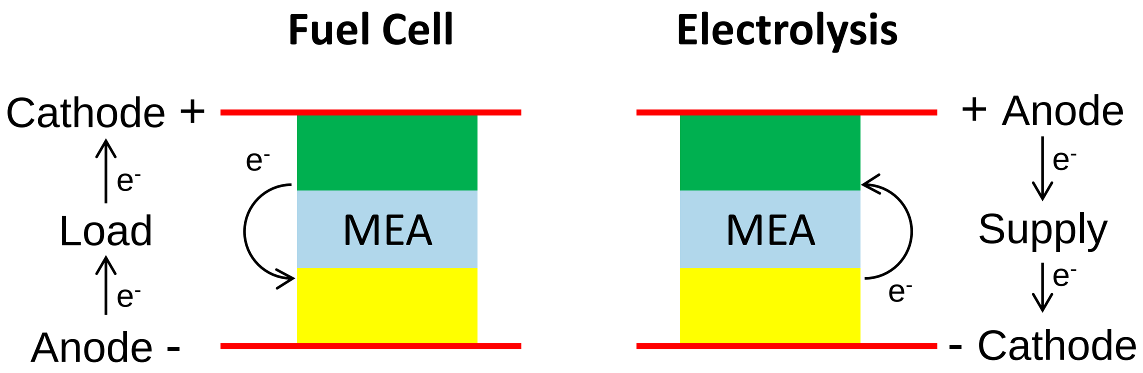


Notes
- Potentially complicated water management
- Proof-of-concept demonstrations
  - Multiple chemistries
  - Aeronautic systems in flight configurations
  - Space systems in laboratory configurations
- Commercial H_2/air systems available
  - Uninterruptable Power Supply (kW·hr to GW·hr)
  - On-time performance primary requirement
  - No roundtrip or specific energy requirements

Unitized Regenerative Fuel Cells

Constant Gas

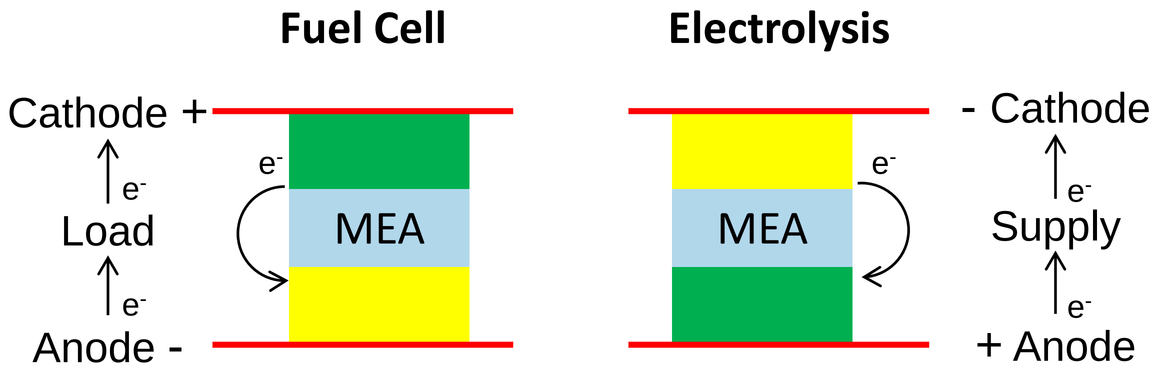
Change Ion Flow Direction



Advantages	Disadvantages
Constant Gas Location • Simple Fluidic Systems • Fast mode transition times	Complex Power Electronics • Power Switching Required • Diode Protection Required

Constant Electrode

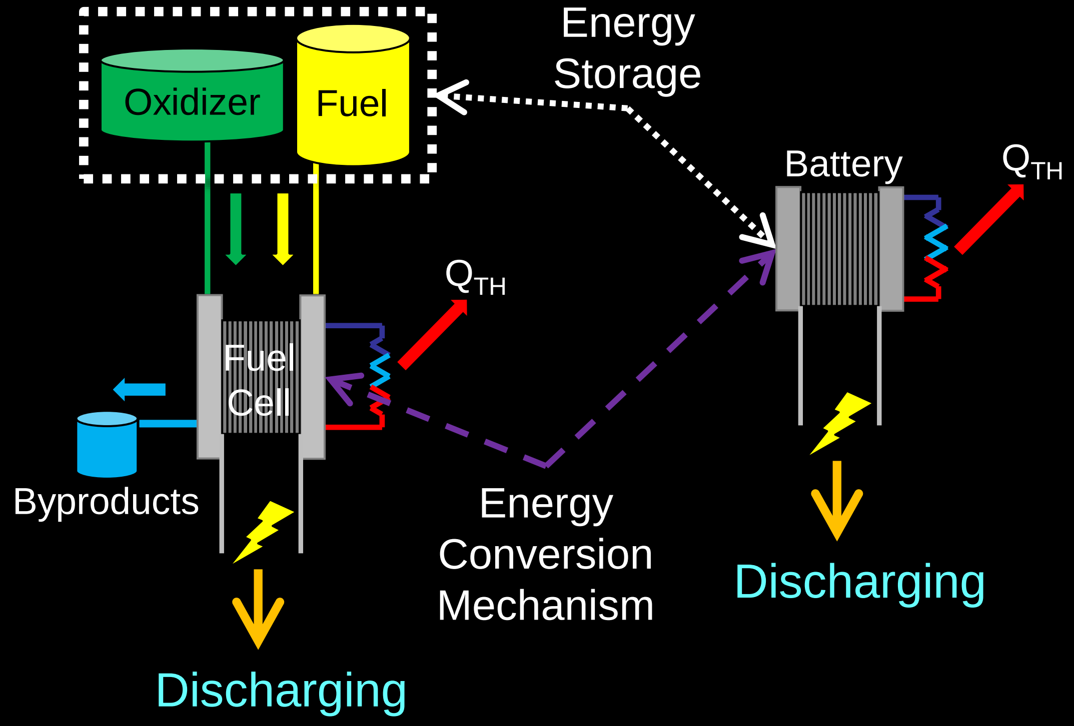
Preserve Ion Flow Direction



Advantages	Disadvantages
Simple Power Electronics • Optimized Flow Channel designs	Complex Fluidic System • Significant safety mitigation efforts required (Required mitigations prevent this configuration in crewed missions) • Very slow mode transition times

Primary Fuel Cells vs. Primary Battery

Electrical Power to enable and augment exploration activities



Primary Metric = Specific Power (W / kg)

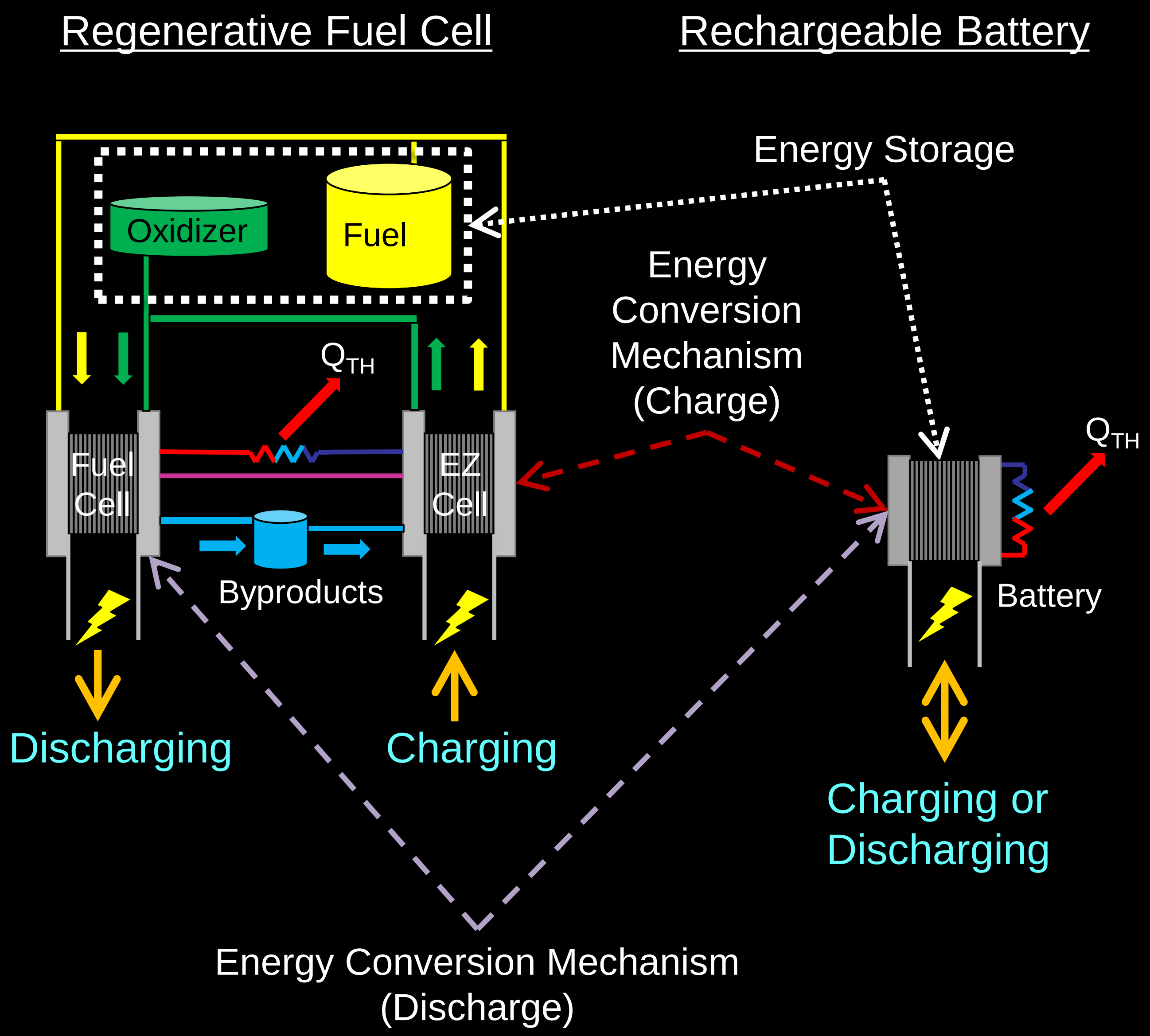
Batteries store energy intimately with the energy conversion mechanism

Primary fuel cells store energy remotely from the energy conversion mechanism

- Different Hazards and Mitigations
  - Batteries sensitive to Thermal Runaway
  - Fuel Cells sensitive to Material Compatibility and Process Fluid management issues
- Different Voltage to State-of-Charge (SoC) relationships
  - Battery voltage dependent on quantity of stored energy
  - Fuel Cell voltage independent of quantity of stored energy
- Different Scalability
  - Battery system specific energy determined by chemistry and packaging
  - Fuel Cell system specific energy determined by quantity of reactants and packaging

Regenerative Fuel Cell vs. Rechargeable Battery

Energy Storage enabling and augmenting exploration activities

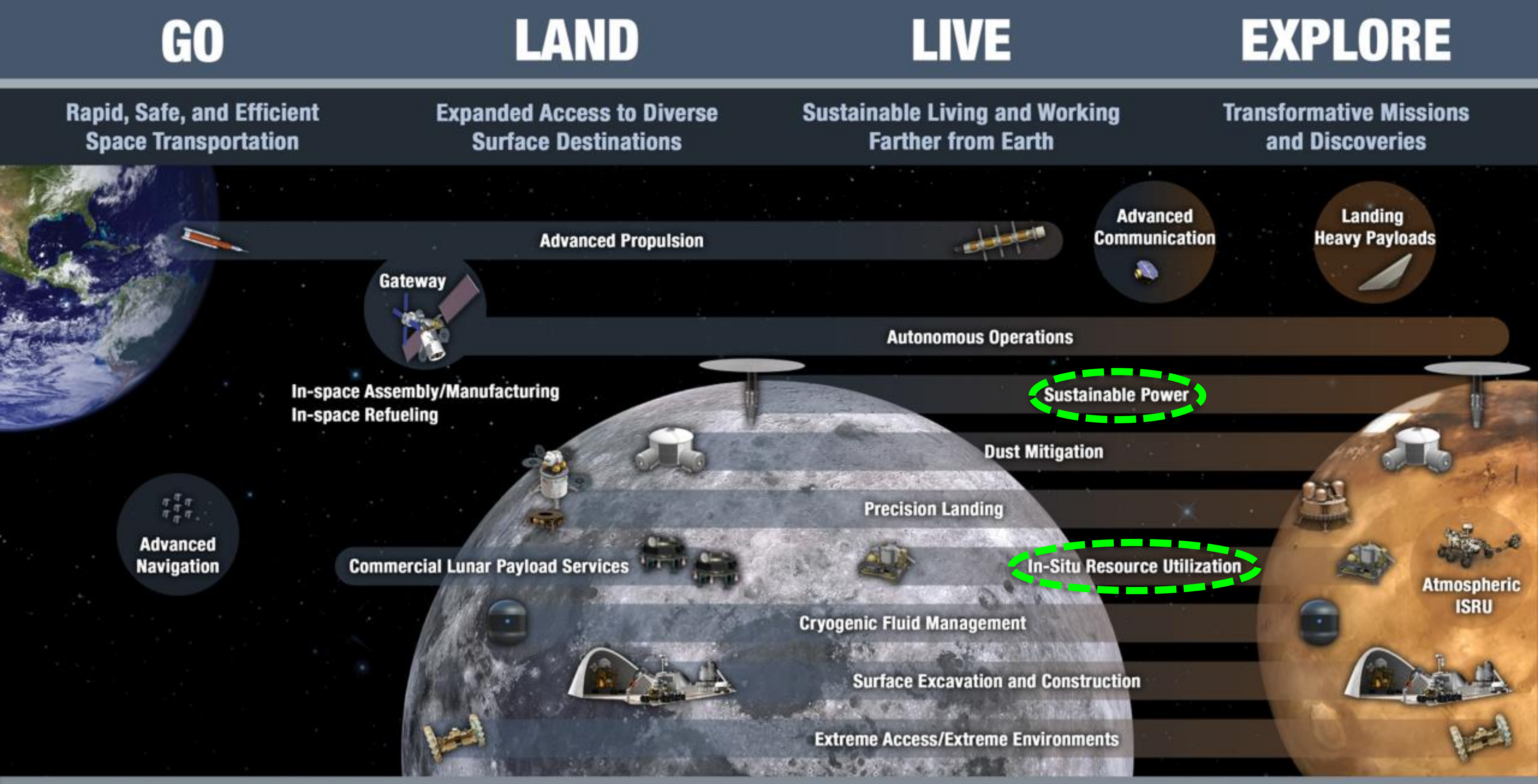


Primary Metric = Specific Energy (W·hr / kg)

Rechargeable batteries store energy intimately with the energy conversion mechanism

Regenerative fuel cells (RFCs) store energy remotely from the energy conversion mechanisms

- Different Hazards and Mitigations
  - Batteries sensitive to Thermal Runaway
  - RFC have very complicated supporting systems
- Different Voltage to State-of-Charge (SoC) relationships
  - Rechargeable battery voltage dependent on quantity of stored energy
  - RFC discharge voltage independent of quantity of stored energy
- Different Recharge/Discharge capabilities
  - Battery rates determined by chemistry and SoC
  - Fuel Cell and electrolyzer independently “tunable” for mission location


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
Advanced Propulsion
Advanced Communication
Landing Heavy Payloads
Gateway
Autonomous Operations
In-space Assembly/Manufacturing
In-space Refueling
Sustainable Power
Dust Mitigation
Advanced Navigation
Precision Landing
Commercial Lunar Payload Services
In-Situ Resource Utilization
Atmospheric ISRU
Cryogenic Fluid Management
Surface Excavation and Construction
Extreme Access/Extreme Environments

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

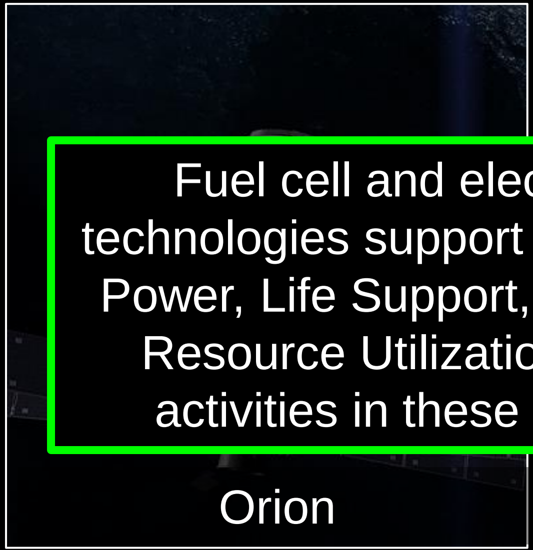
The Artemis Program Snapshot


Space Launch System


Commercial Lunar Payload Services

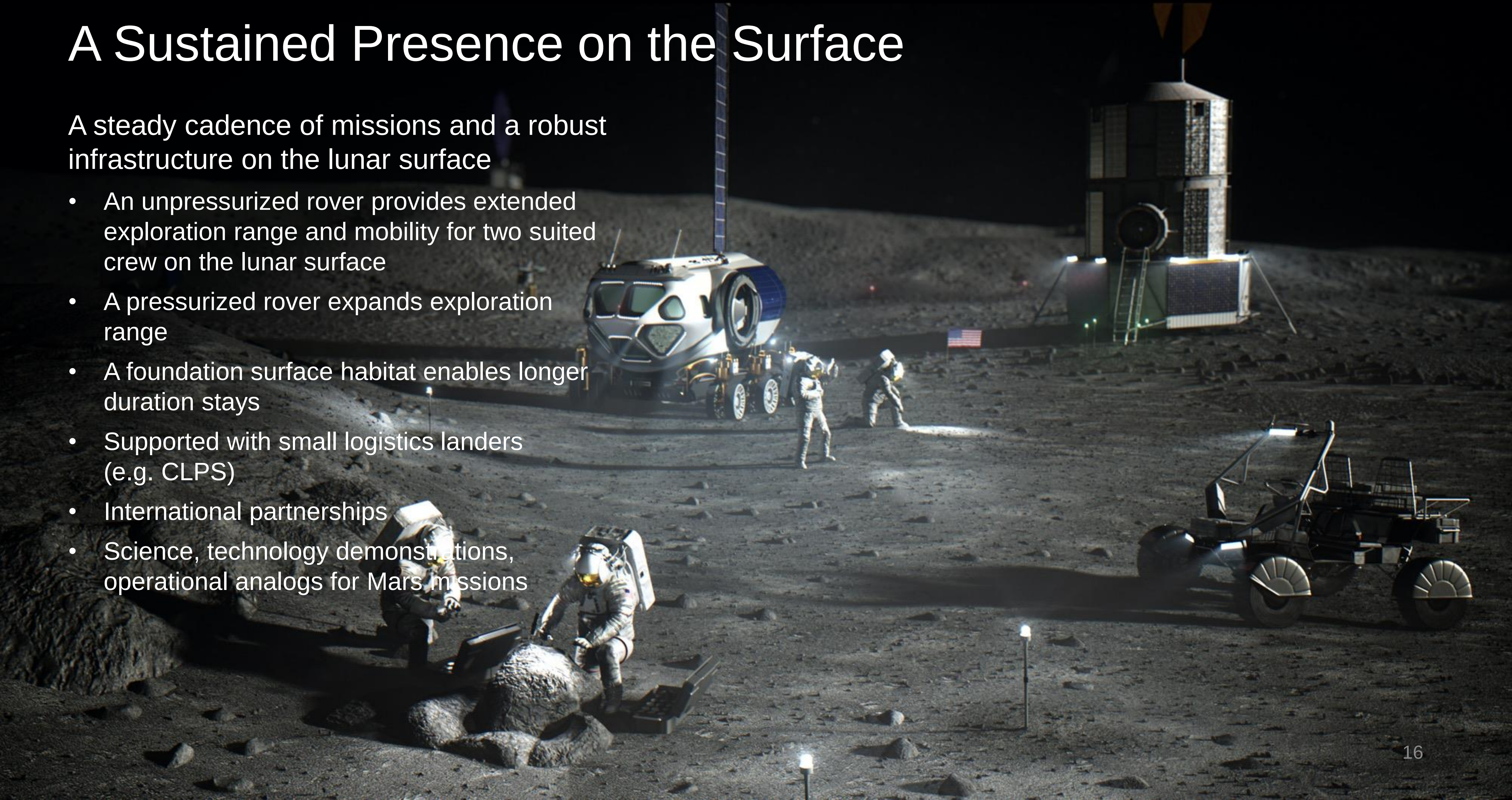

The Gateway in lunar orbit

Fuel cell and electrolysis technologies support Sustainable Power, Life Support, and In-situ Resource Utilization (ISRU) activities in these domains


Orion


First woman and first person of color to the Moon


Surface systems



A Sustained Presence on the Surface

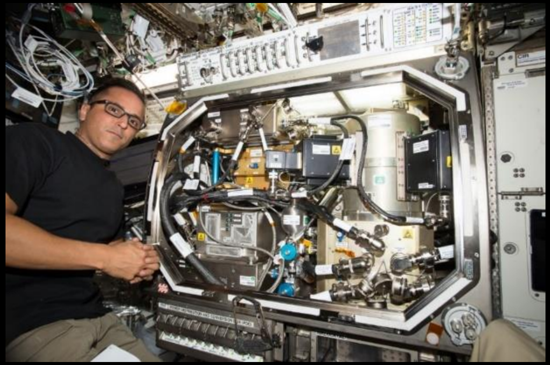
A steady cadence of missions and a robust infrastructure on the lunar surface

- 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

Electrochemical Activities Within NASA

Reactant 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*



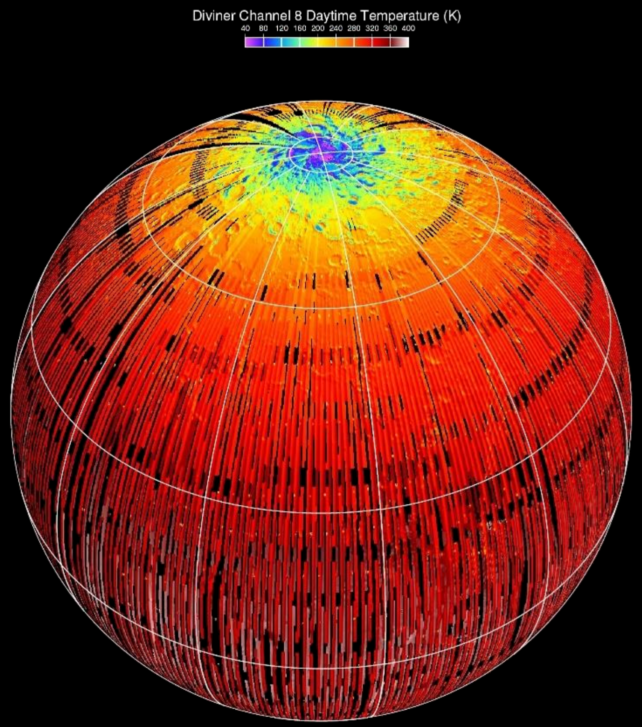
Transfer and Storage

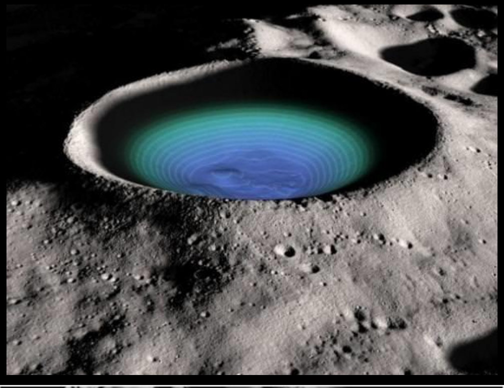
- *Hydrogen Management in space*
  - *Cryogenic Fluid Transfer in μ-gravity*
- *Extend storage duration of cryogenic fluids*
  - *Zero-Boil-off Tanks*
  - *High-efficiency Efficiency Cryo-coolers*

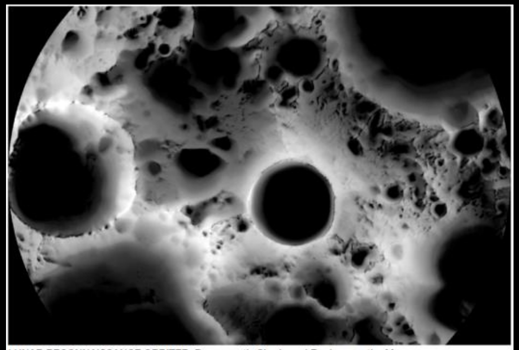
Power Production

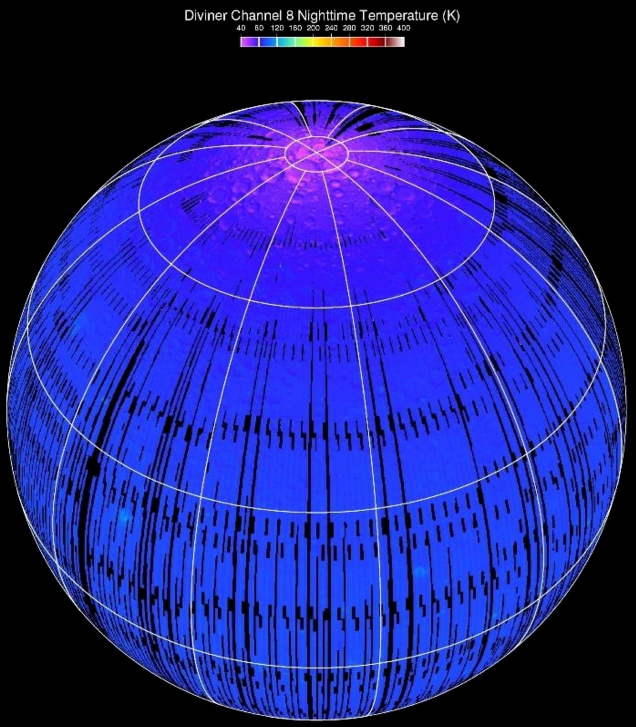
- *Propellants*
  - *Launch Vehicles*
  - *Mars/Lunar Landers*
- *Fuel hydrogen-based fuel cells*
  - *Lunar/Mars surface systems*
  - *Urban Air Mobility*
- *Metal Processing*
- *Refrigerants*

The Lunar Environment






LUNAR RECONNAISSANCE ORBITER: Permanently Shadowed Regions on the Moon



- The average temperature on the Moon (at the equator and mid latitudes) varies from 90 Kelvin (-298 ºF or -183 ºC), at night, to 379 Kelvin (224 ºF or 106 ºC) 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 ºF or -238 ºC)
- 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**

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

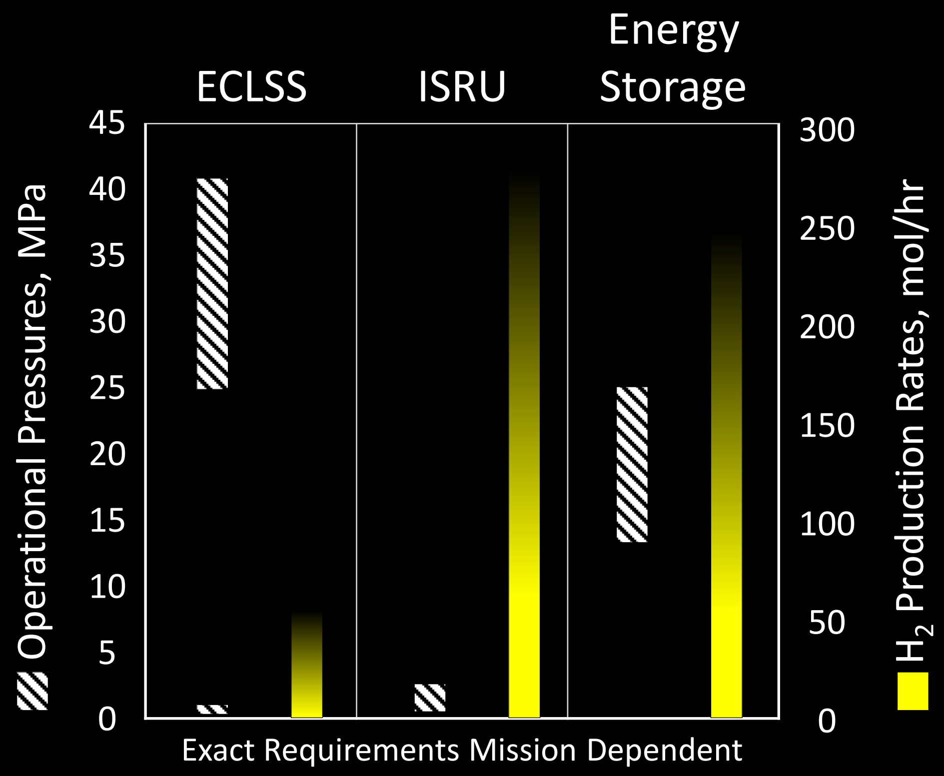
- Fuel cells can provide energy storage to provide power in locations near humans where nuclear power may not be an option
- Regenerative fuel cell can provide continuous power for longer-term operations (such as the lunar night)
- Hydrogen enables energy storage and transportation in the challenging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

Reactant Generation

Electrolysis

- *Electrochemically dissociate water into gaseous hydrogen and oxygen*
- *ECLSS*
    - *Unbalanced Design ($H_2 << O_2$)*
    - *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*

Notional Electrolysis Requirements



All applications Power and Mass Constrained

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.)*

Reactant Generation Activities

1. Proton Exchange Membrane (PEM) Electrolysis
   - ISS Advanced Oxygen Generator Assembly (AOGA)
   - Regenerative Fuel Cell Project
   - High Pressure PLSS O_2 Tank Recharge
   - IHOP PEM Water Electrolysis/Clean-up – Paragon
   - Lunar Propellant Production Plant (LP3) – Skyre
   - Metal Oxidation Warming System Fuel Cell - Maxar

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

Funding Sources

NASA Funds	BAA
Tipping Point / ACO	SBIR / STTR

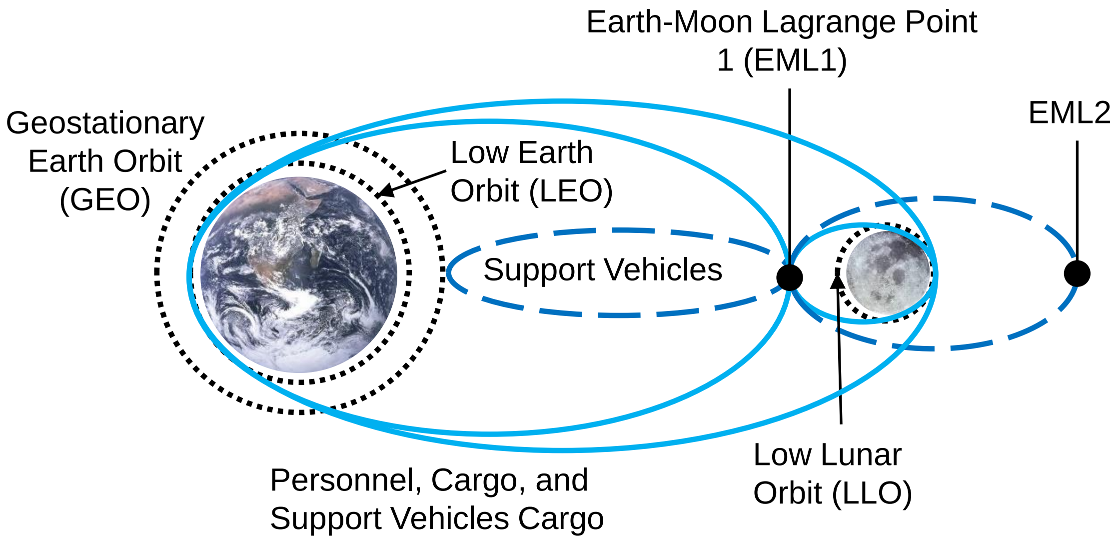
3. Alkaline (Dirty Water) Electrolysis
   - Advanced Alkaline Electrolysis (AAE) – Teledyne
   - Advanced Alkaline Reversible Cell (AARC) – pH Matter
   - Bifurcated Reversible Alkaline Cell for Energy Storage (BRACES) – pH Matter

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)
   - Production of Oxygen and Fuels from In-Situ Resources on Mars (O2PM) - OxEon Energy LLC
   - Integrated Architecture Trade Studies on ISRU Technologies for Human Space Exploration - University of Illinois
   - 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

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

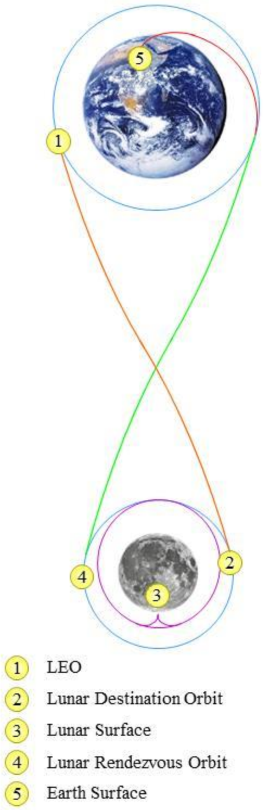


Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

- 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

Reactant Transfer and Storage

Transporting Hydrogen and Oxygen through cis-lunar space is very 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

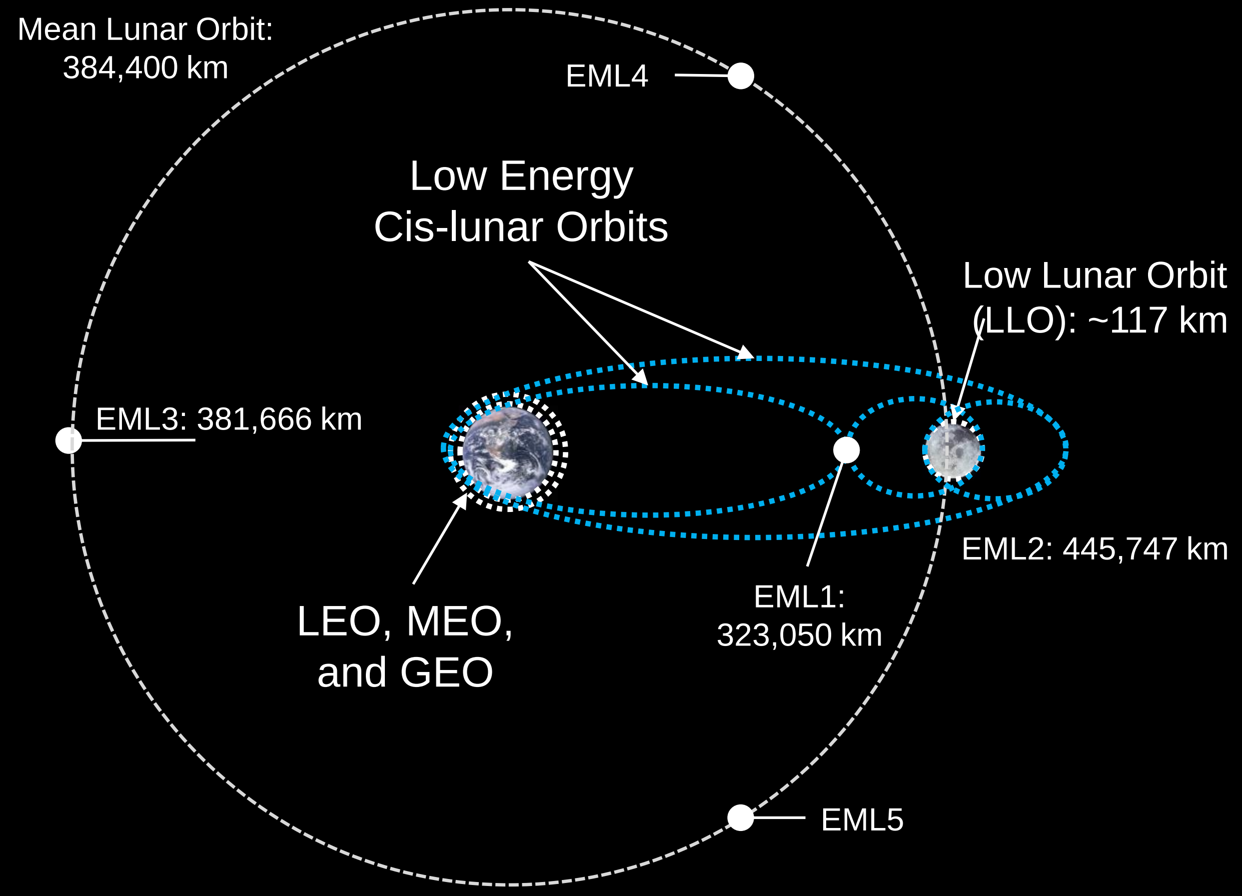
Complex Thermal Environment

Very low H_2 liquid transition temperatures

Radiation only available heat sink

Very large temperature differences between sun-facing and deep-space facing surfaces

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

Reactant 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
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

Power Generation and Storage

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)*

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

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)*

Power Production 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

Funding Sources

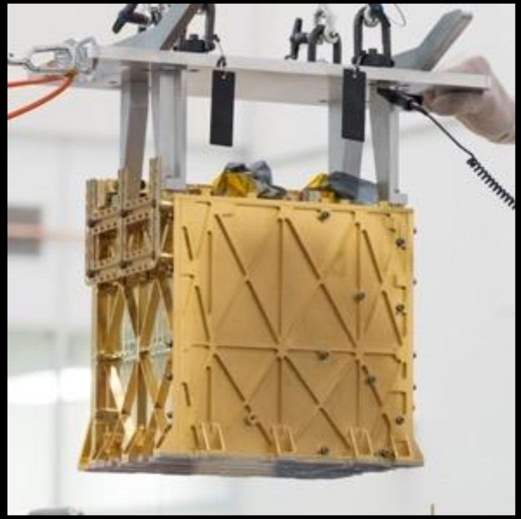
NASA Funds	BAA
Tipping Point / ACO	SBIR / STTR

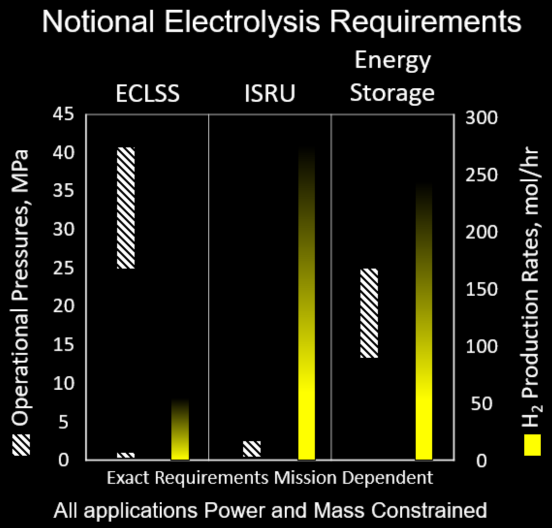
Presentation Summary

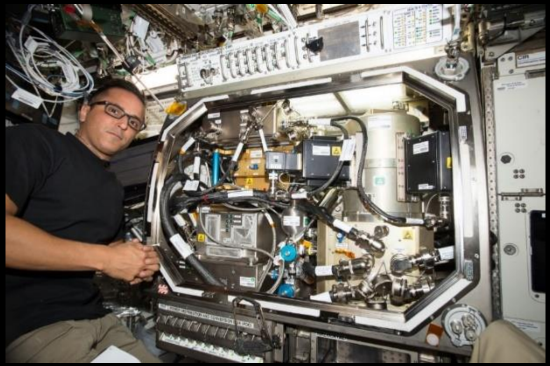
- High Level Overview of fuel cell and electrolysis technologies

- Provide a background of NASA fuel cell and electrolysis activities technologies for Aerospace applications:
    - Reactant generation
    - Reactant transfer and storage
    - Power and Energy Storage

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







Questions


Thank you for your attention.