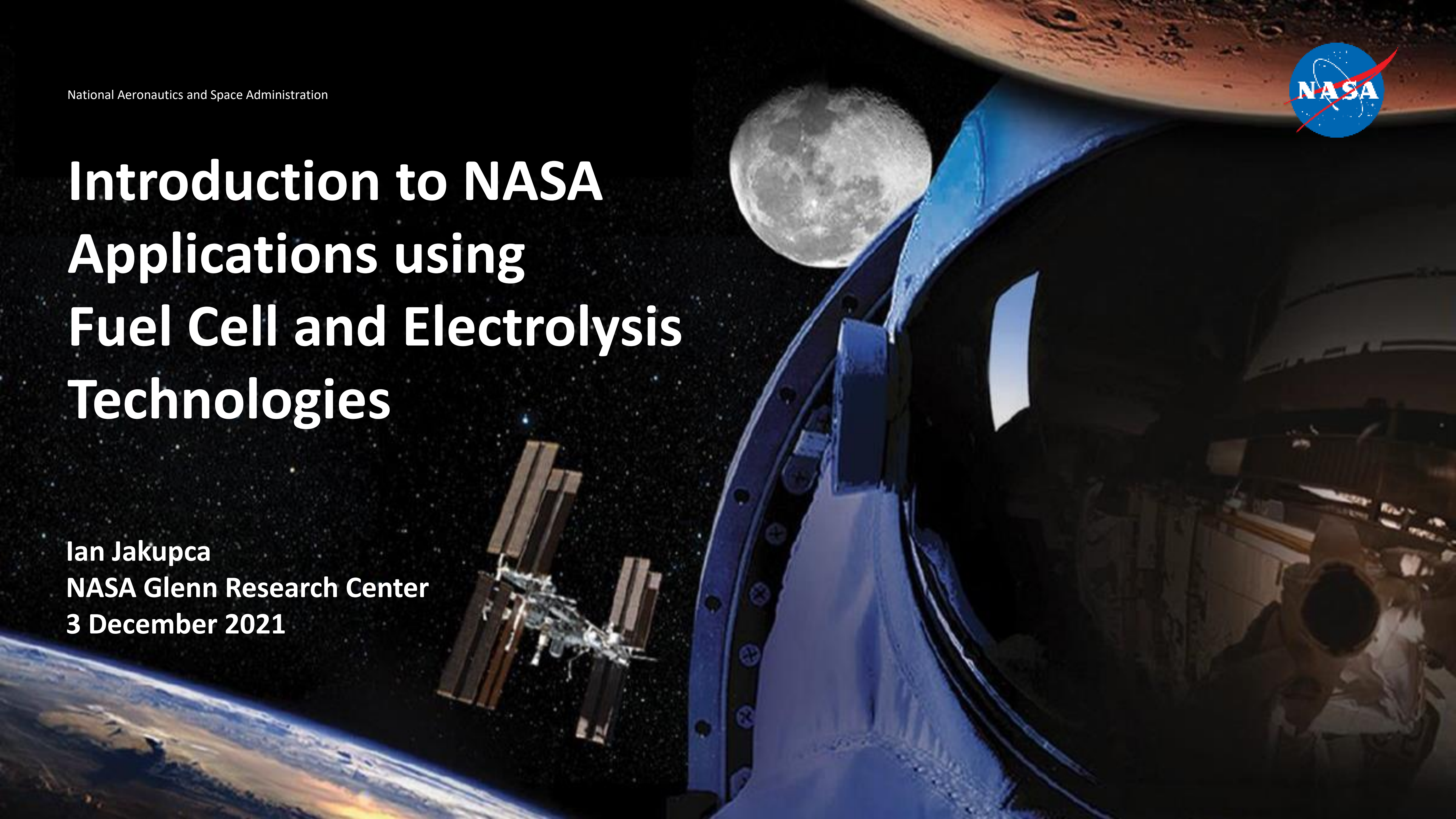
National Aeronautics and Space Administration

Introduction to NASA Applications using Fuel Cell and Electrolysis Technologies



Ian Jakupca
NASA Glenn Research Center
3 December 2021

Presentation Overview

Presentation Objective:

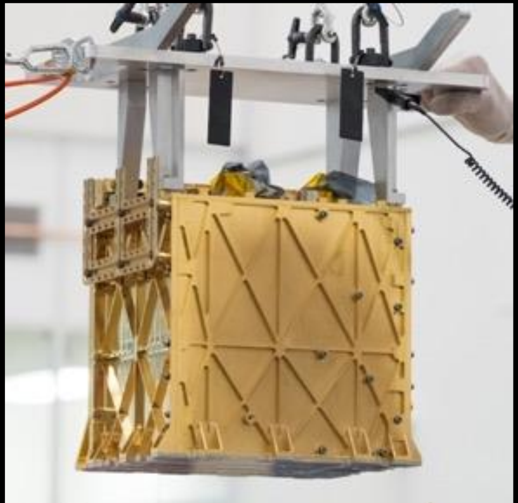
Summarize the fuel cell and electrolysis activities funded by NASA within the following domains:

- Power / Energy Storage
- In Situ Resource Utilization (ISRU)
- Environmental Control and Life Support (ECLSS)

This presentation has the following sections:

1. Agency plans relevant to fuel cells and electrolysis
2. Fuel Cells for Power and Energy Storage
3. Electrolysis for ISRU
4. Regenerative Fuel Cells

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.

GO

Rapid, Safe, and Efficient Space Transportation

LAND

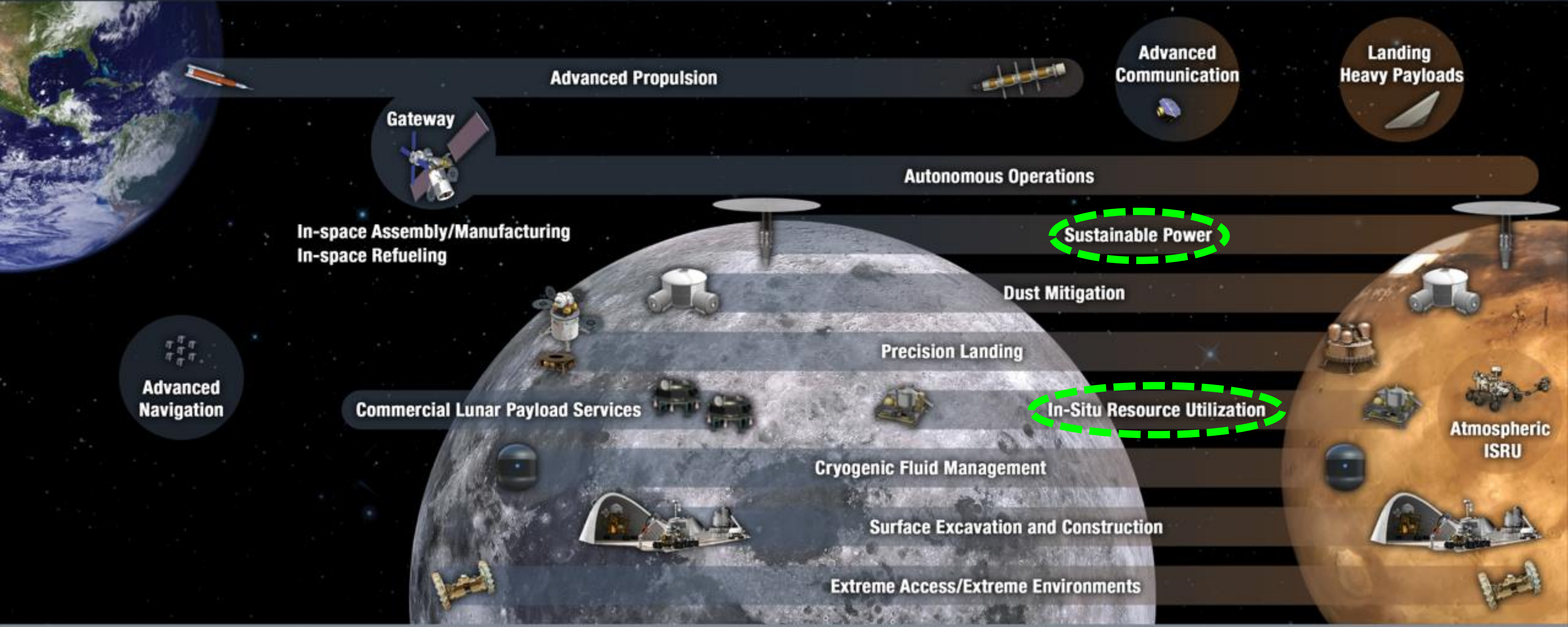
Expanded Access to Diverse Surface Destinations

LIVE

Sustainable Living and Working Farther from Earth

EXPLORE

Transformative Missions and Discoveries



Advanced Propulsion

Gateway

Advanced Communication

Landing Heavy Payloads

Autonomous Operations

In-space Assembly/Manufacturing
In-space Refueling

Sustainable Power

Dust Mitigation

Precision Landing

Advanced Navigation

Commercial Lunar Payload Services

In-Situ Resource Utilization

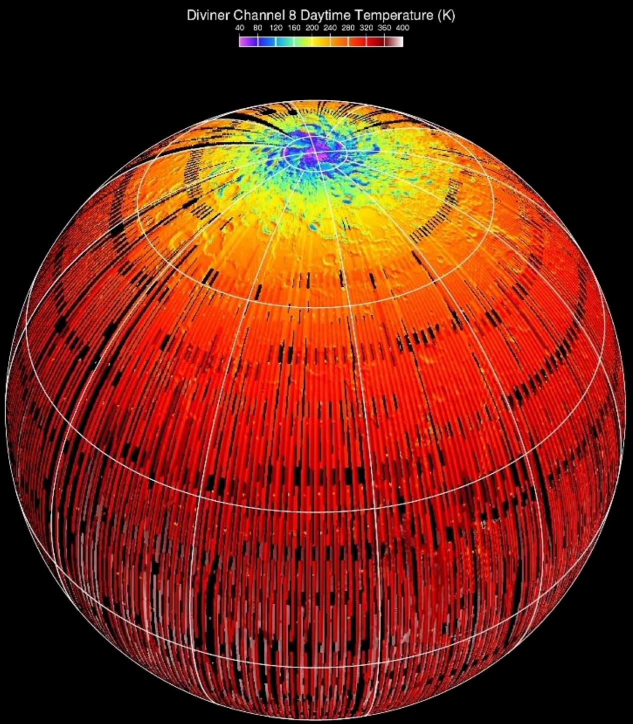
Atmospheric ISRU

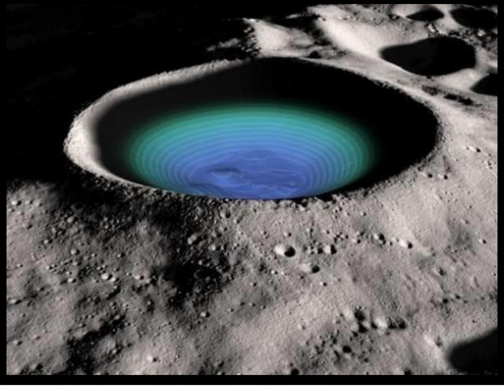
Cryogenic Fluid Management

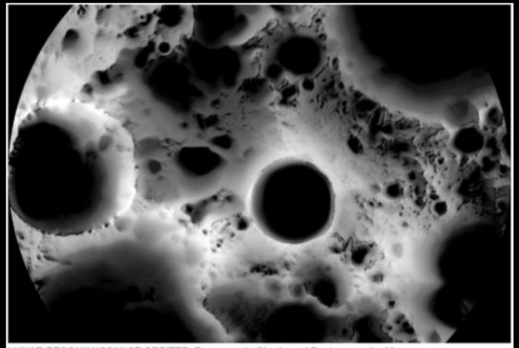
Surface Excavation and Construction

Extreme Access/Extreme Environments

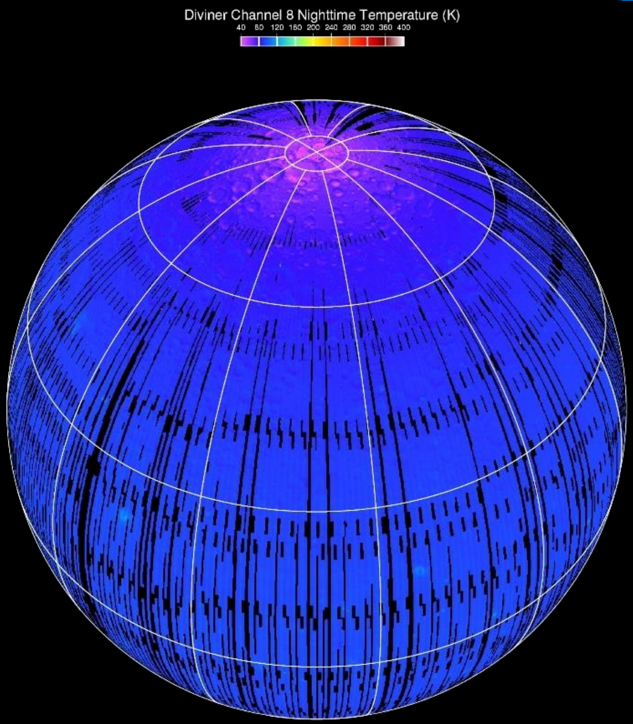
The Lunar Environment







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 °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**

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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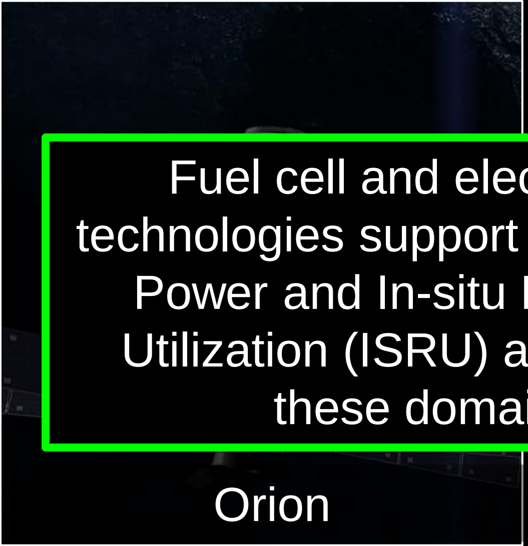
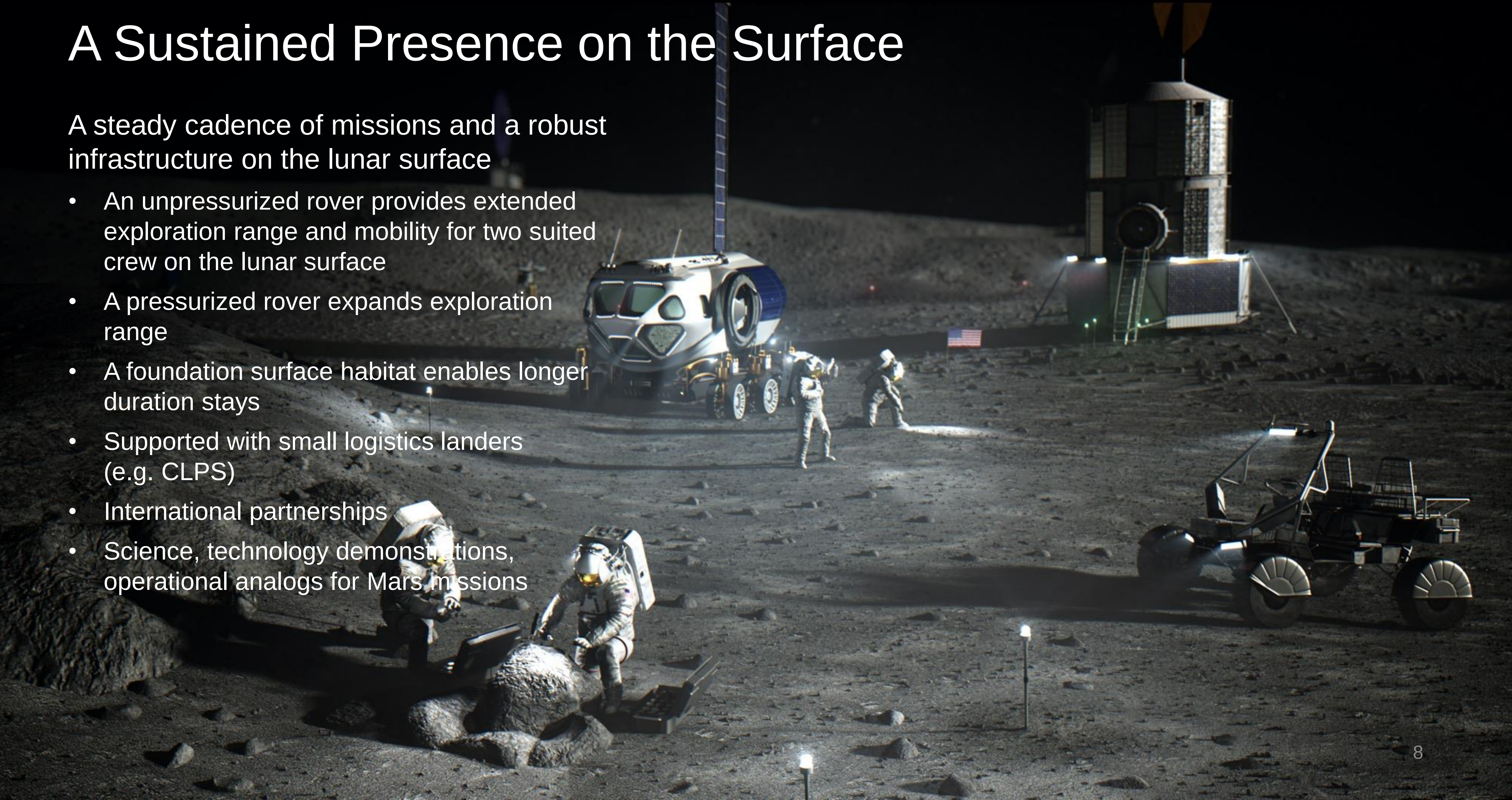
The Gateway in lunar orbit


Orion


First woman and first person of color to the Moon


Surface systems

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



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

Hydrogen Generation

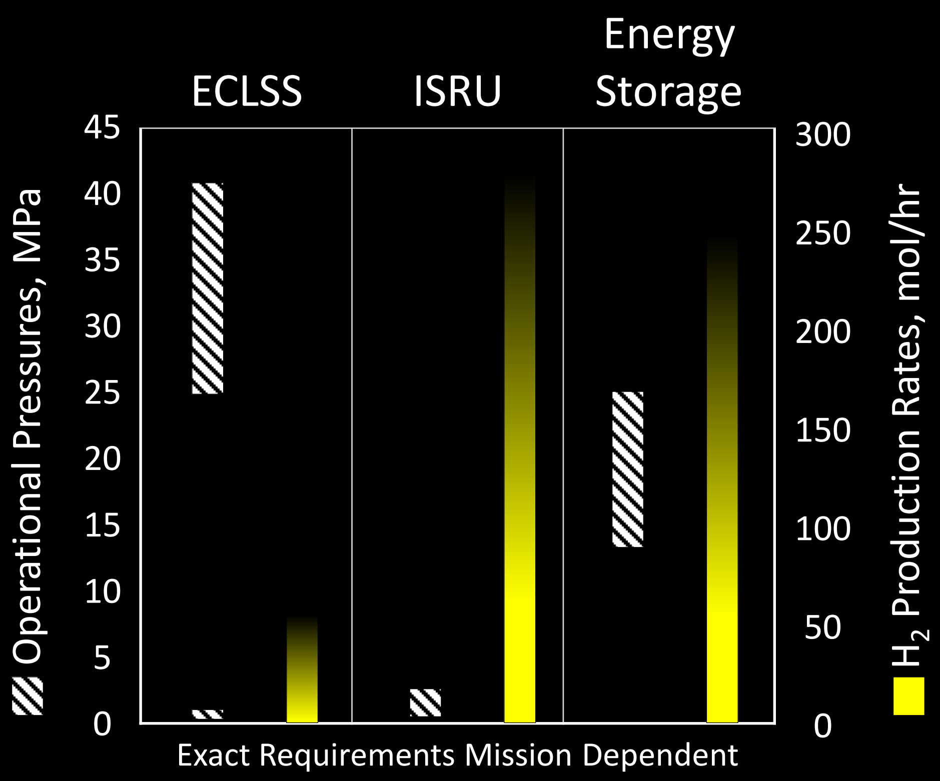
Electrolysis

- *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*

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



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)*

Energy Storage

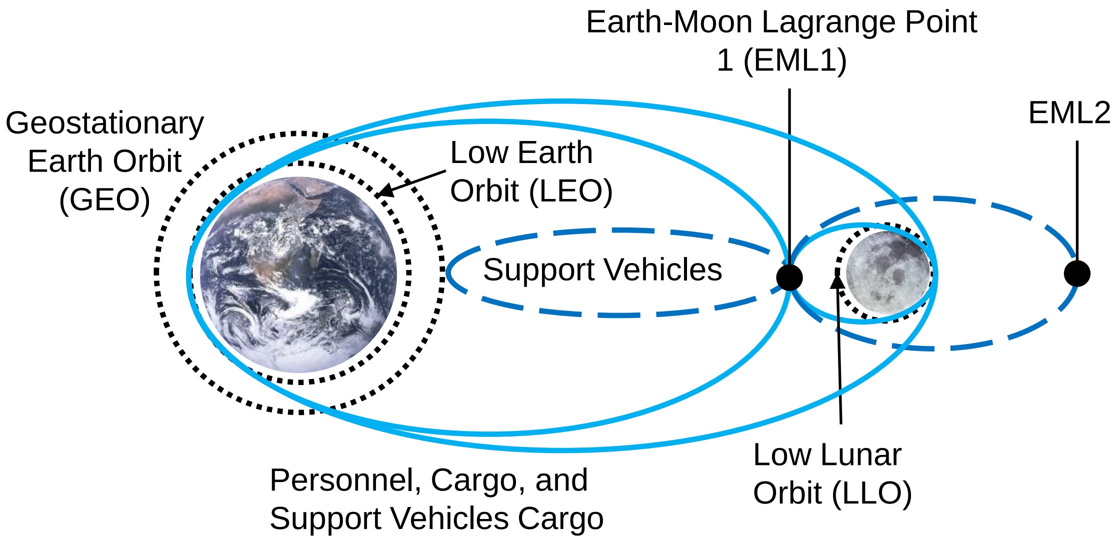
- *High specific energy (W·hr/kg) means to store and release electrical and thermal energy*
    - *Lunar night: ~100 hrs (south pole) to 367 hrs (equator)*
    - *Waste heat helps systems survive the lunar thermal environment (-173°C to +105°C)*
    - *Targeting ≥ 50,000 hours maintenance interval*

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

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

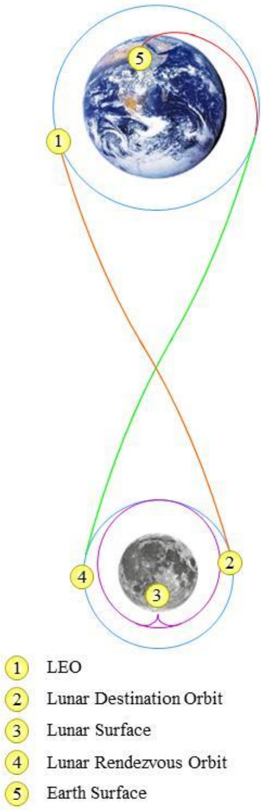


Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent

- 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

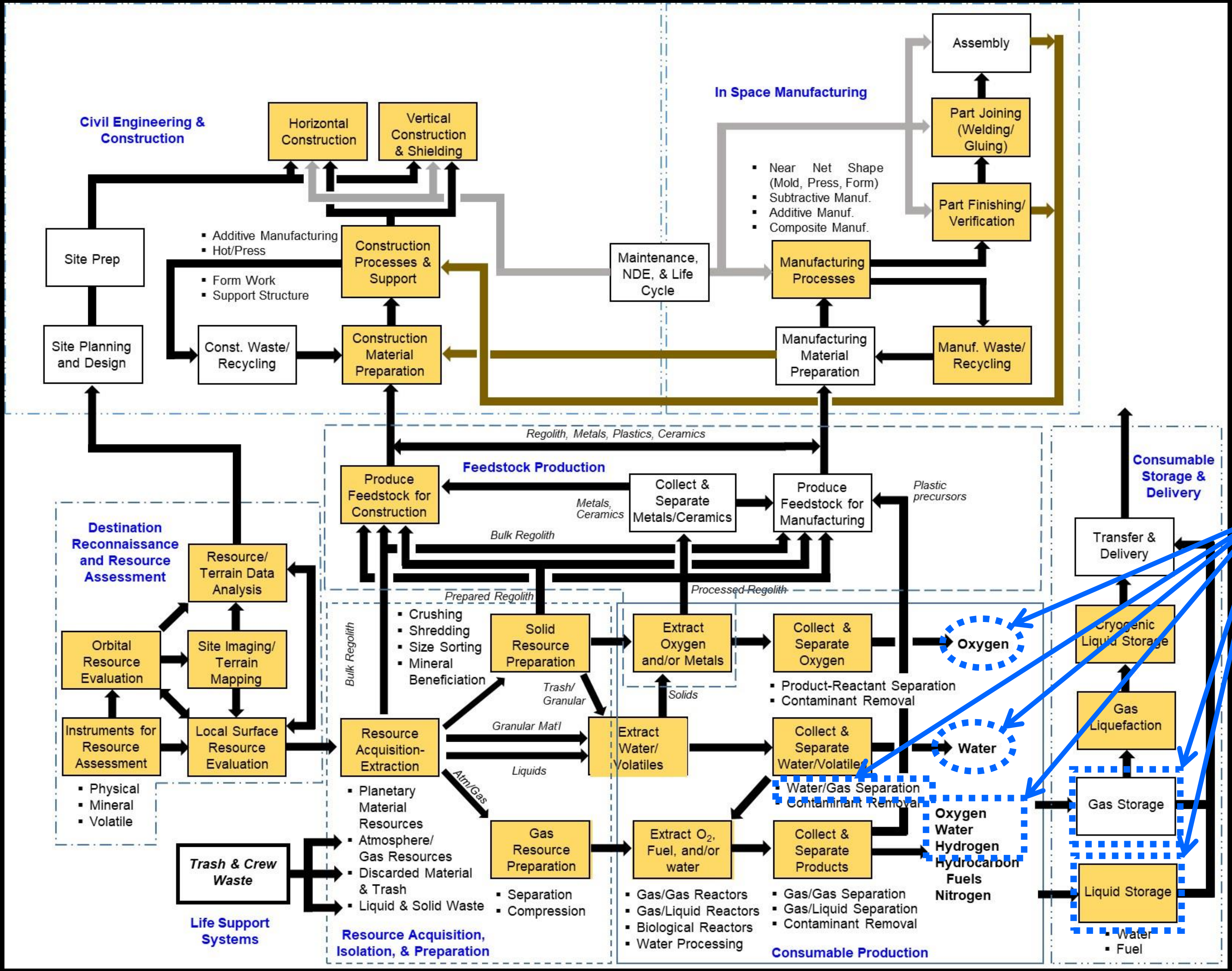
- Crew Ascent Stage (1 way): 3 to 6 mT O_2
- Single Stage (both ways): 40 to 50 mT O_2/H_2



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

ISRU and Surface Excavation & Construction

ISRU Functional Block Diagrams

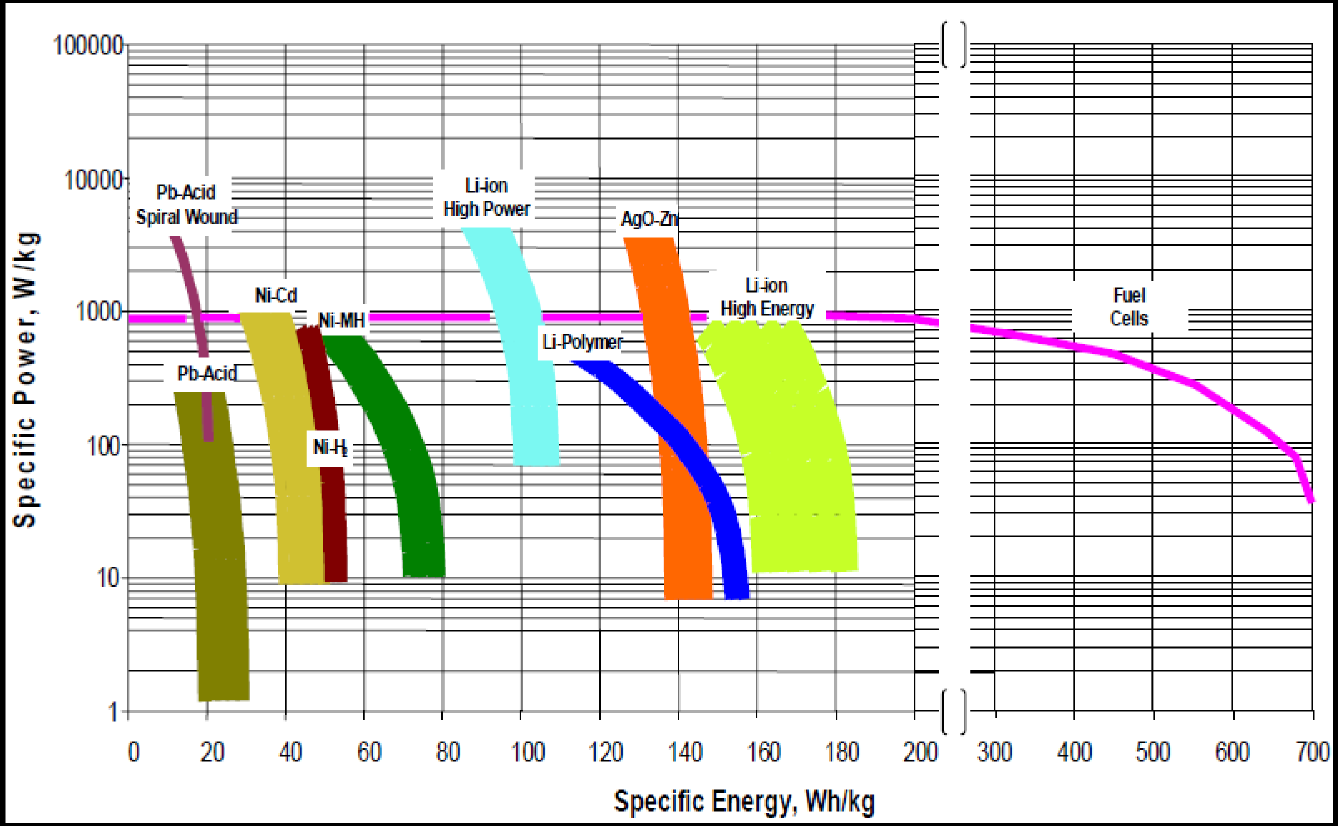


🟨 = funded work

How RFC Technologies Apply to ISRU

- Potential Integration Opportunity:
  - Shared Technologies with common Sub-systems
  - Chemical plant with multiple processes
  - Integrate multiple Sub-systems
  - Power Generation Capability
- Commonalities include:
  - Generation of Humidified H_2 / O_2 gasses
  - Dehumidification of H_2 / O_2 gases
  - Multiphase Fluid Management
  - Complex Thermal Management
  - Storage of H_2 / O_2 gases

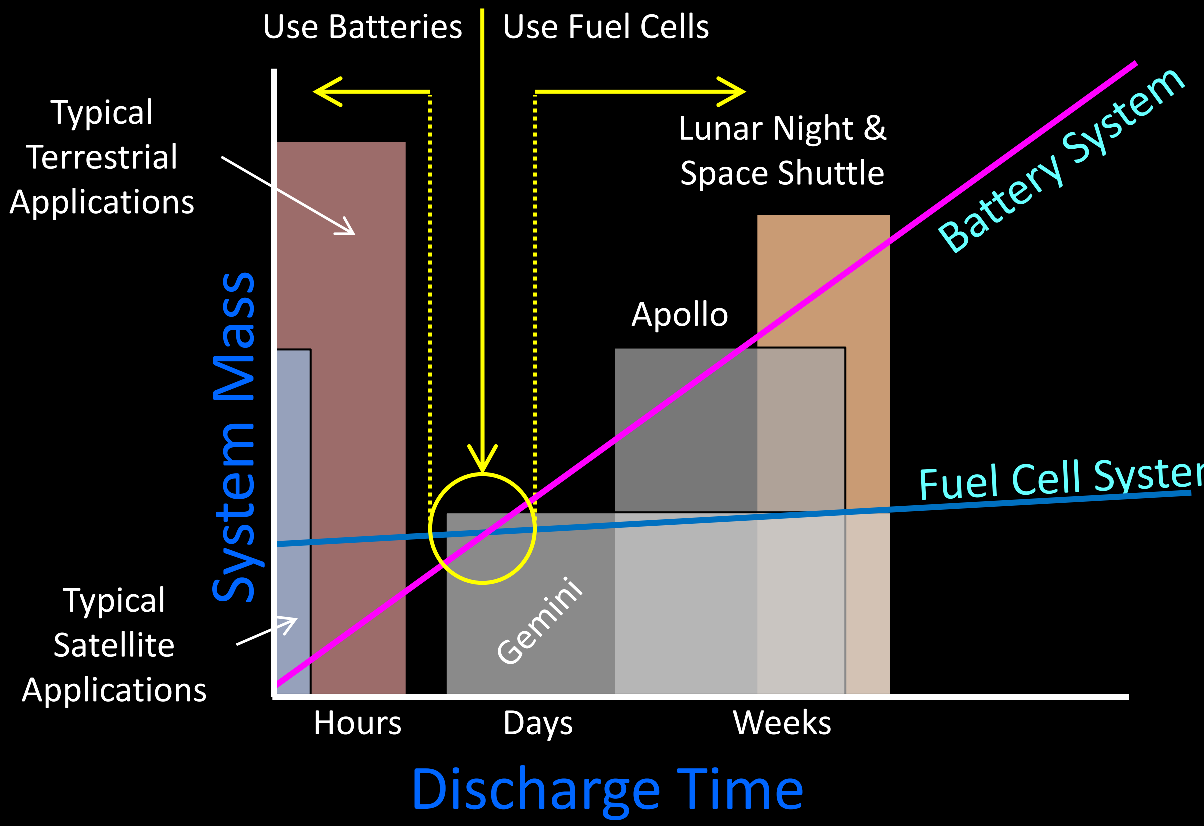
Electrochemical Energy Storage Options



Data presented at Office of Space Science Energy Storage Review by Robert Staniewicz and Kamen Nechev of SAFT, Goddard Space Flight Center, 26 Sept 2002

Trade Required

(~10 to 18 hours, Energy dependent)

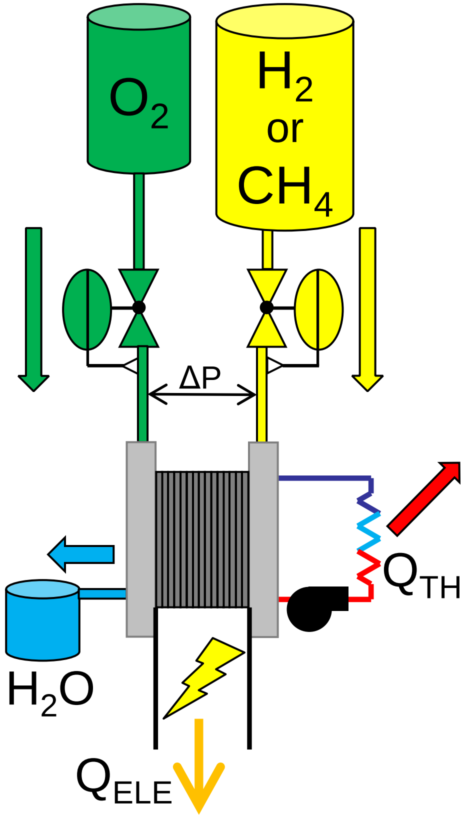


Electrochemical Systems for Space

Primary Fuel Cell

Discharge Power

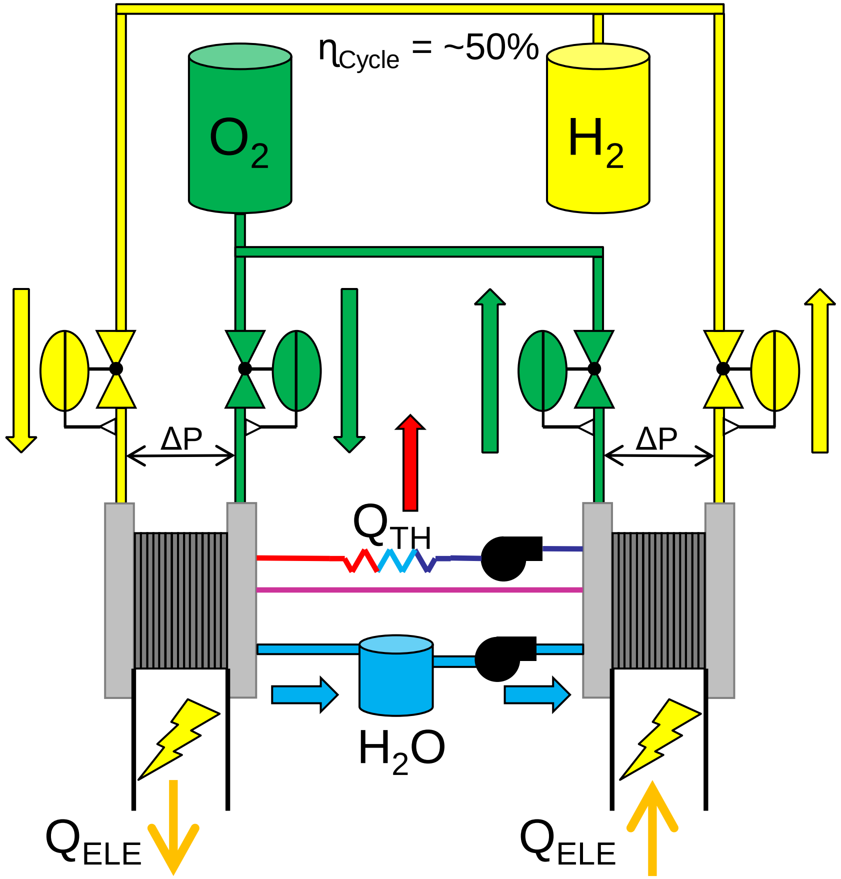
$2H_2 + O_2 \rightarrow 2H_2O + 4e^- + Heat$



Discharging

Regenerative Fuel Cell

Energy Storage



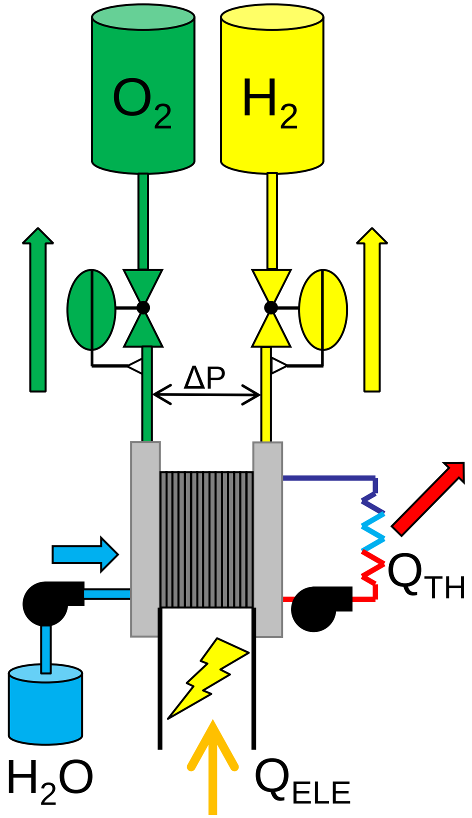
Discharging

Charging

Electrolysis

Chemical Conversion

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

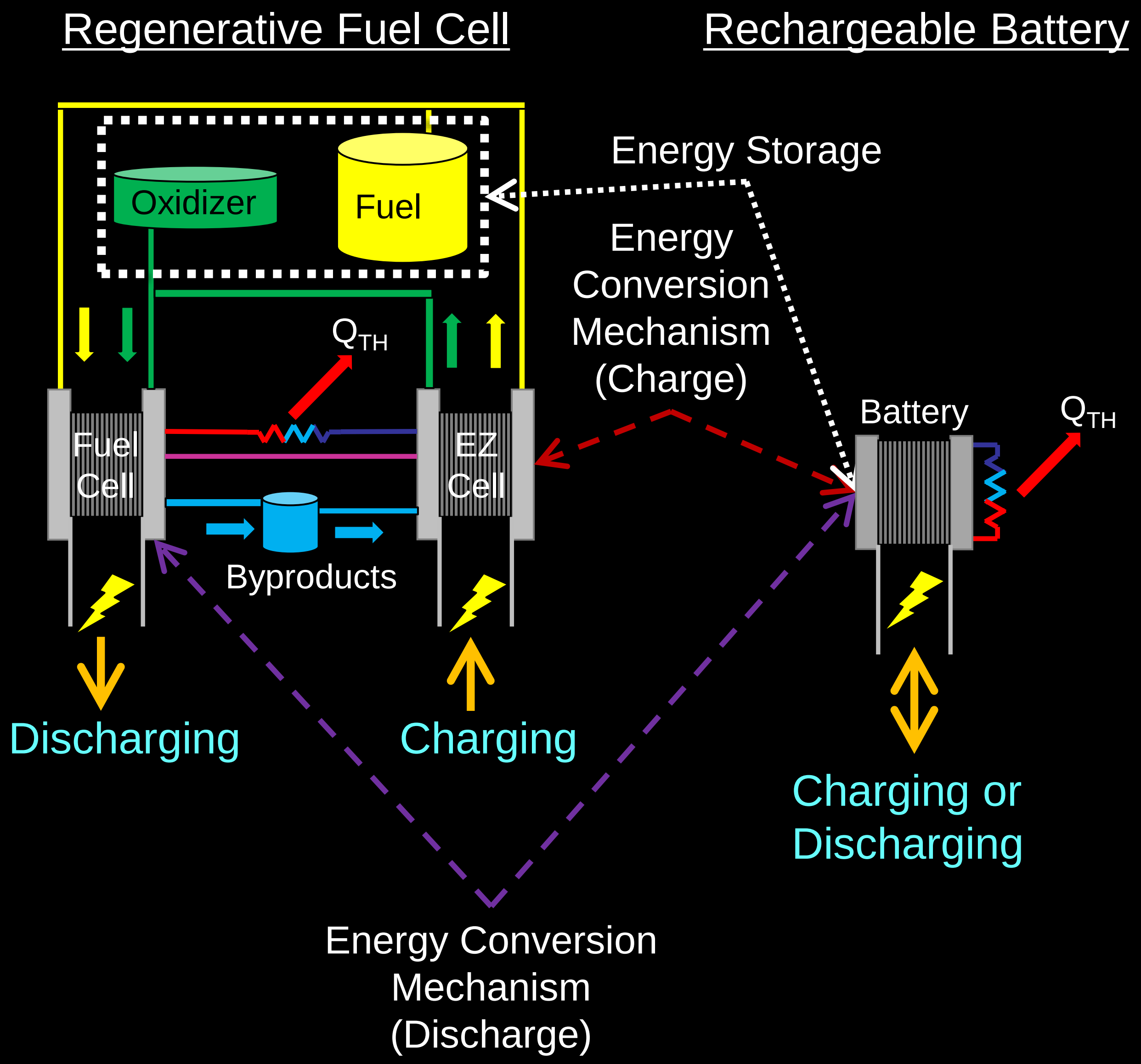


Charging

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

Regenerative Fuel Cell vs. Rechargable Battery

Energy Storage enabling and augmenting exploration activities



Rechargeable batteries store energy intimately with the energy conversion mechanism

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

This difference results in:

- 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

Regenerative Fuel Cell Project
Technical Summary

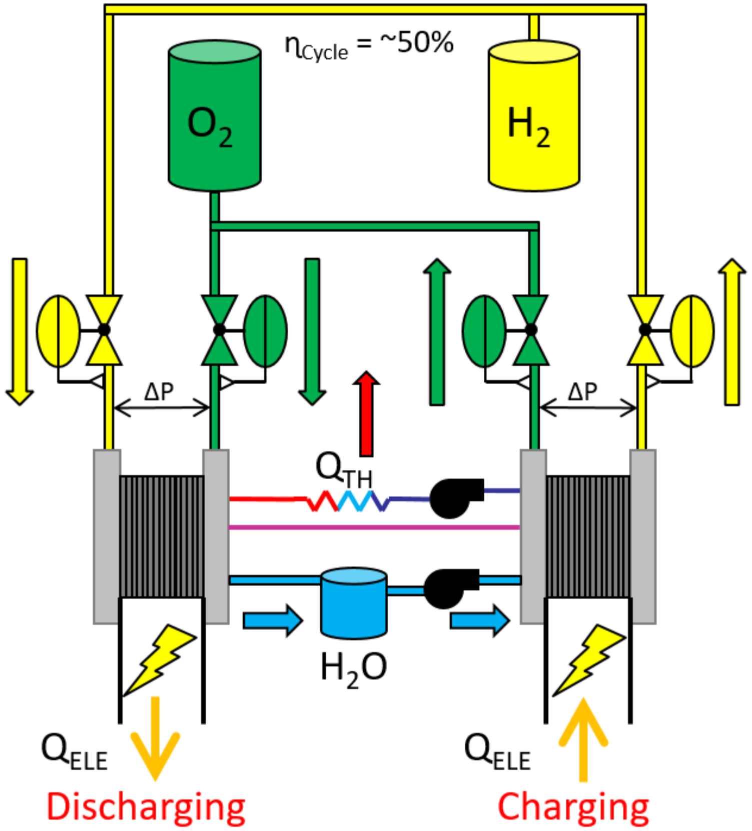
Technology development, ground demonstration effort; not a flight project

System Requirements

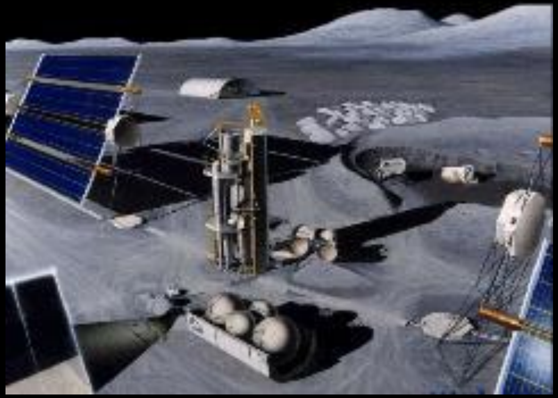
- Must *demonstrate* net energy storage capability within a simulated lunar environment
- Fully packaged automatic system with an identified a path to a packaged specific energy > 320 W•hr/kg (project goal > 550 W•hr/kg)

RFC System: Nominal 100 W_e discharge power on a 28 ± 5% V voltage bus

- Fuel Cell (FC) Stack
  - Support load profile ranging from 0 to 400 W with a bus potential > 9 Vdc
  - FC stack capable of sustained operation on >15% inert contaminants (He, N_2, etc.) in either/both reactant streams
- Electrolyzer (EZ) Stack
  - Self-pressurize from ambient to 1800 psig (potential 2500 psig) balance pressure ($H_2 \approx O_2$)
  - Maximum charge power ≈ 1.5 kW
- TVAC Environment
  - Temperatures = < -173 ^{o}C to +105 ^{o}C
  - Pressures = Ambient to < 10^{-5} Torr



Presentation Review



- NASA Plans for Fuel Cell and Electrolysis Technologies
  - Power / Energy Storage
  - In Situ Resource Utilization (ISRU)
  - Environmental Control and Life Support (ECLSS)

- Mission Arc
  - Develop on Earth
  - Deploy on the Moon
  - Prepare for Mars

- Technology Discussion
  - Electrolyzers
  - Rechargeable Batteries vs Regenerative Fuel Cells
  - Fuel Cells
  - Regenerative Fuel Cells

Thank you for participating