



Fuel Cell Research and Development for Earth
and Space Applications

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Department of Energy
Annual Merit Review
14 June 2018



Presentation Outline

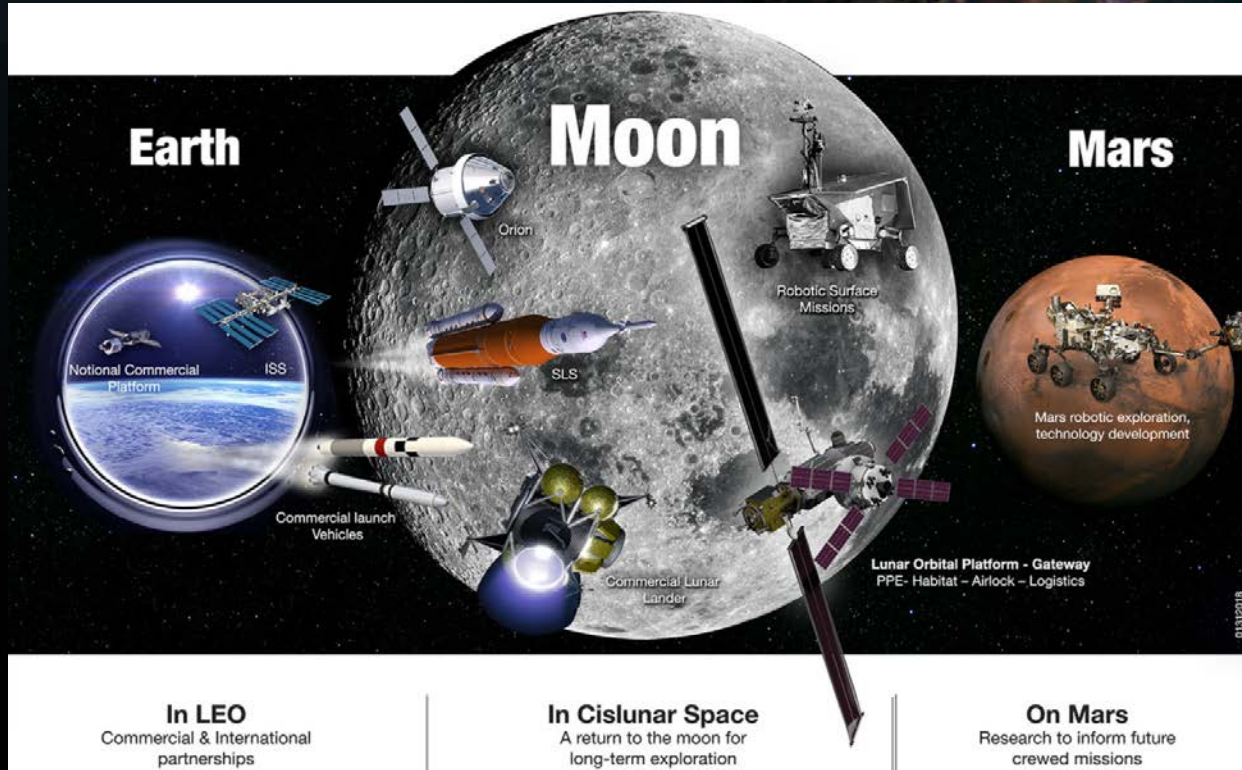


- NASA – Overview and Scope
- Definitions
 - Types of Fuel Cell Systems
 - Energy Storage: Batteries vs. Regenerative Fuel Cells (RFC)
 - Comparison of Fuel Cell Technologies
 - Portability of Terrestrial technologies to Aerospace applications
- NASA applications benefitting from Electrochemistry
- Active NASA Fuel Cell research
 - Power Generation
 - Commodity Generation
 - Energy Storage
- Review



OVERVIEW AND SCOPE

NASA – Overview and Scope



01/13/2018



NASA Programmatic Domains

Science

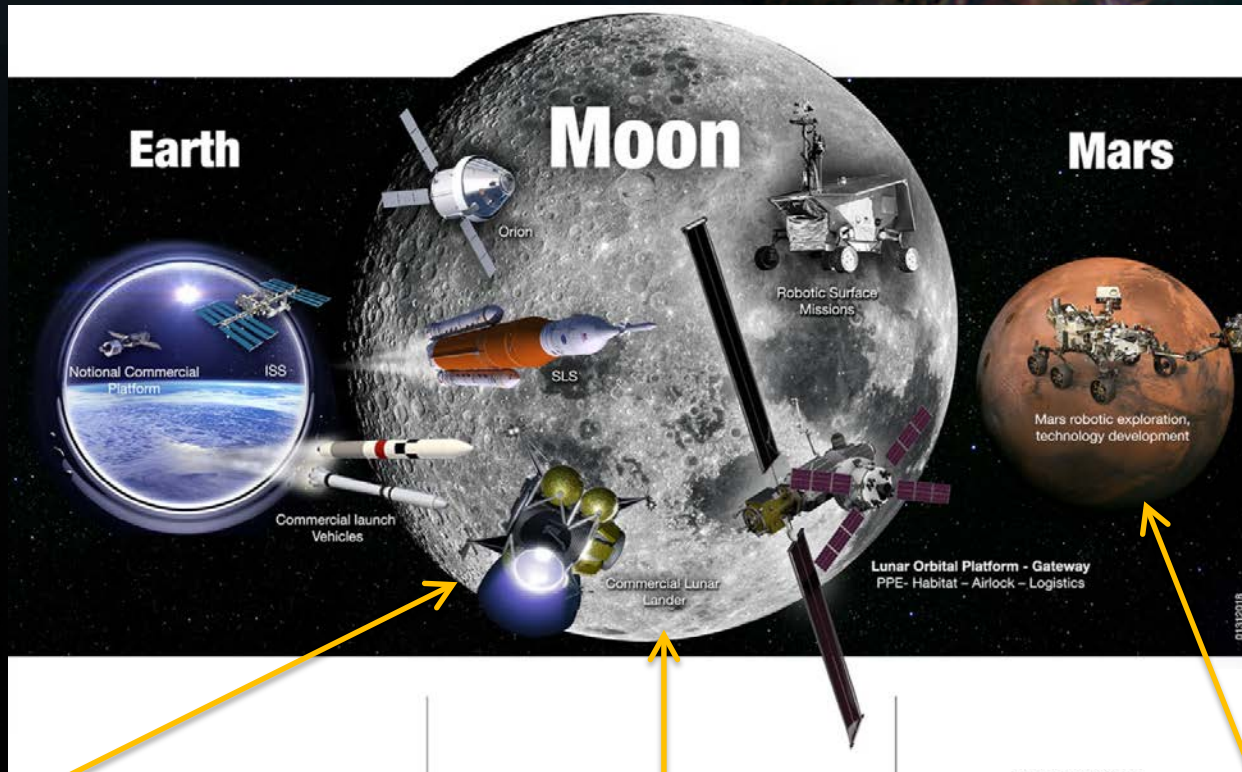
Aeronautics

LEO and Spaceflight Operations

Deep Space Exploration

Exploration Research and Technology

NASA Applications benefitting from Electrochemistry



Electrified Aircraft



Landers



Lunar Outposts



Martian Outposts and Rovers



DEFINITIONS

Definitions: Types of Aerospace Fuel Cell Systems

Primary Fuel Cell

Power Generation



Discharging Only

Description

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

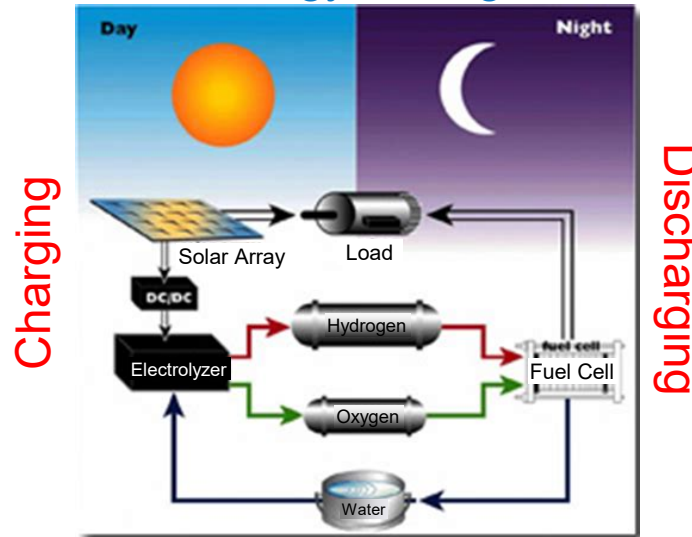
NASA Applications:

Sustained High-Power

- Crewed transit vehicles (Apollo, Gemini, STS, etc.)
- Power-intense rovers/landing platforms

Regenerative Fuel Cell

Energy Storage



Description

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

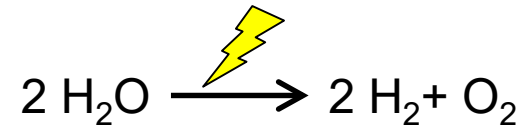
NASA Applications:

Ensuring Continuous Power

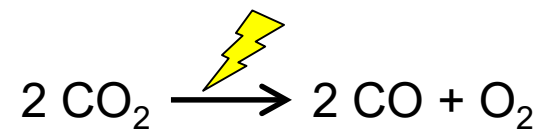
- Surface Systems (exploration platforms, ISRU, crewed)
- Platforms to survive Lunar Night

Electrolysis

Commodity Generation



or



Description

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

NASA Applications:

Life-support, ISRU

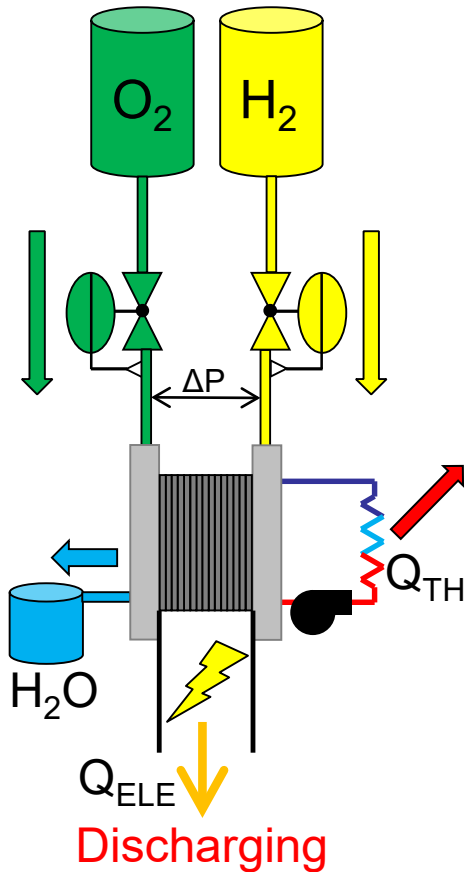
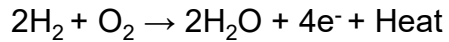
- Oxygen Generation
- Propellant Generation
- Material Processing



Definitions: Types of Aerospace Fuel Cell Systems

Fuel Cell

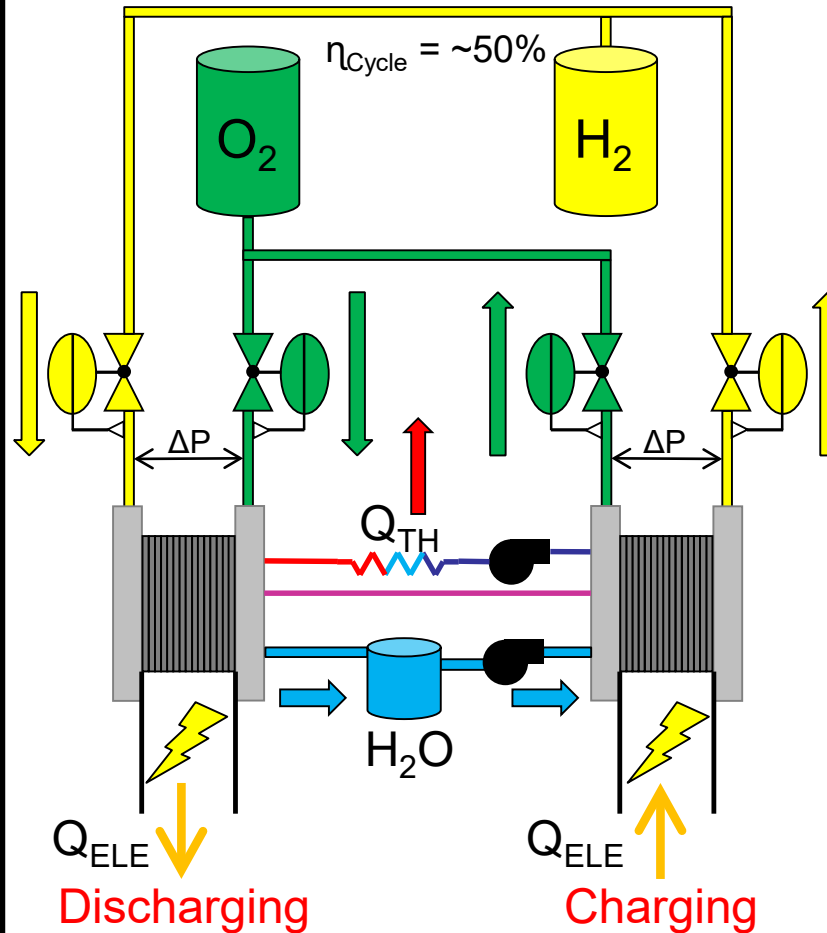
Power Generation



Regenerative Fuel Cell

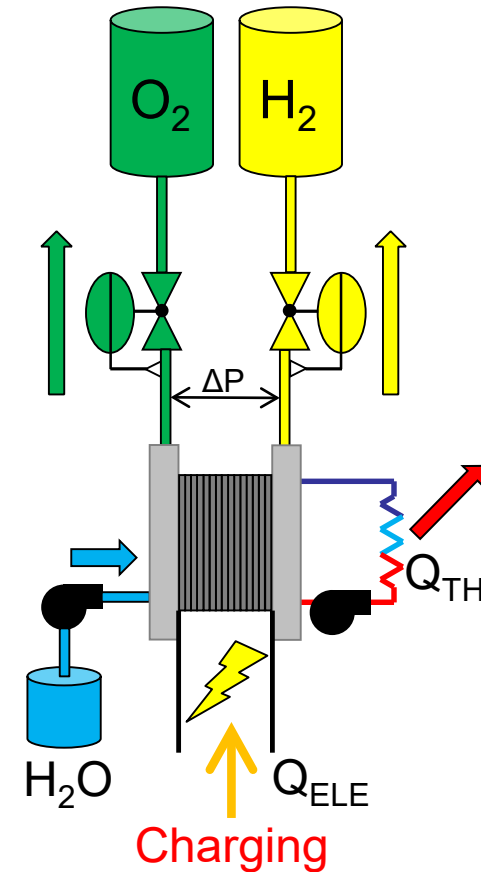
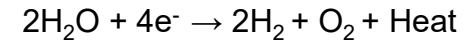
Energy Storage

$$\eta_{\text{Cycle}} = \sim 50\%$$



Electrolysis

Commodity Generation

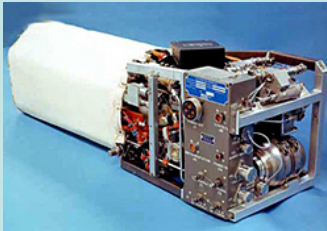


Regenerative Fuel Cell = Fuel Cell + Interconnecting Fluidic System + Electrolysis

Comparison of Fuel Cell Technologies



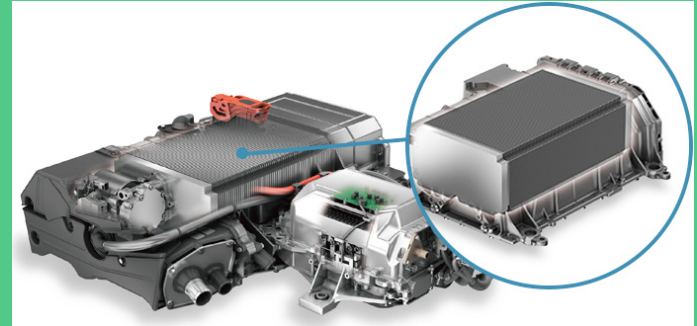
Aerospace



Space Shuttle Fuel Cell Stack
(1979 - 2014)

≠

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

Portability of Terrestrial Technology to Aerospace Applications



		Component	Aerospace TRL Level	Portability of Terrestrial Technology to Aerospace Applications	Remaining Technical Challenge
Electrolyzer Technology	}	Electrochemistry	9	High	
		Materials	5+	High	High Pressure, Mass
		Seals	5+	High	High Pressure, Mass
		Gas Management	5+	Moderate	High Pressure, Mass
Fuel Cell Technology	}	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+	Low	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. Elements of multiple terrestrial applications are required to meet various NASA mission requirements.



RESEARCH ACTIVITIES

NASA Applications benefitting from Electrochemistry



Power Generation: Fuel Cells

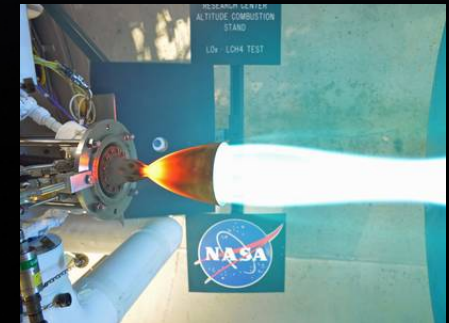
- Electrification of Aircraft
- ❖ High-power rovers
- ❖ Entry/Descent/Landing (EDL)
- Upper Stage Platforms/Long loiter systems

Commodity Generation: Electrolysis

- ECLSS – Oxygen Generation
- ISRU – Propellant Generation
- ISRU – Reduction fluids for Material Processing and Fabrication

Energy Storage: Regenerative Fuel Cell

- Lunar Surface Systems
- Lunar Landers / Rovers
- HALE Un-crewed Aerial Systems (UAS)



NASA Applications researching Electrochemical Systems



Power Generation: Fuel Cells

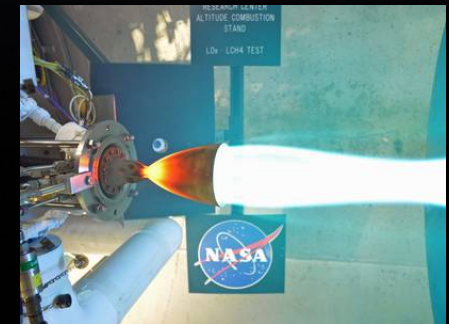
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Energy Storage: Regenerative Fuel Cell

- ❖ Lunar Surface Systems
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Legend

- Hardware Development
- ❖ Analytical Development
- Recent work not funded this Fiscal Year



POWER GENERATION

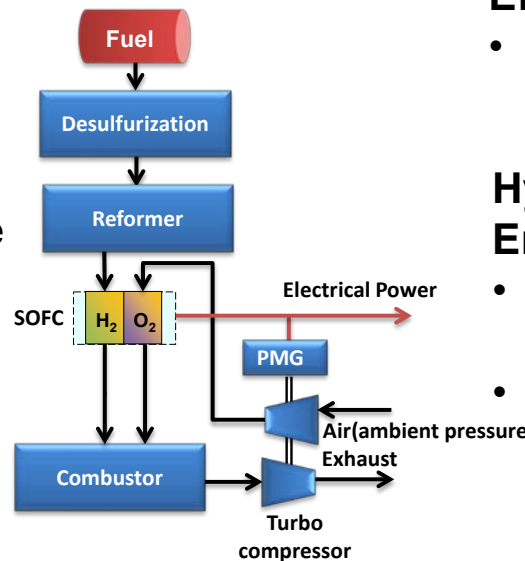
Oxidizer

+ Fuel

+ Electrochemical Reaction

Electrical Power

Power Generation: Fuel Cells Electrification of Aircraft



High-Performance Baseline

- 160-190 knots cruise on 130-190kW
- 1100+ pounds for motor & energy system

Efficient Powertrain

- Turbine-like power-to-weight ratio at 90+% efficiency

Hybrid Solid Oxide Fuel Cell Energy System

- >60% fuel-to-electricity efficiency
- Designed for cruise power; overdrive with moderate efficiency hit at takeoff and climb power

- Convert experimental X-57 to an electric aircraft
- Integration of key technologies to yield compelling performance to early adopters
 - Useful payload, speed, range for point-to-point transportation
 - Energy system that uses infrastructure-compatible reactants, allowing for immediate integration
 - High efficiency for compelling reduction in operating cost
- Early adopters serve as gateway to larger commercial market

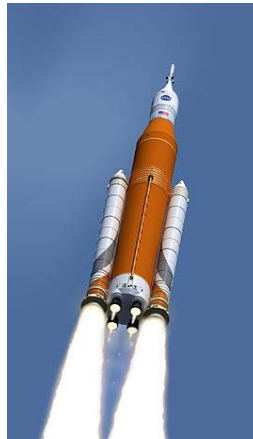
Primary Objective: **Demonstrate a 50% reduction in fuel cost** for an appropriate light aircraft cruise profile (payload, range, speed, and altitude).

Power Generation: Fuel Cell Analytical Activities



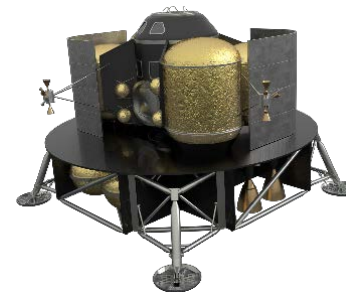
High Power Fuel Cells

- ◆ **Concept:** Crewed transit vehicles, crewed rovers, or rovers with energy-intensive experiments
- ◆ **Application Power:** 1 kW to >10 kW
- ◆ **Future activities:** Laboratory testing of next-generation air-independent stacks ranging from 250 W to 1.2 kW on pure and propellant-grade reactants
- ◆ **Special Notes:**
Recent advances demonstrated autonomous operation and tolerance to vibration loads at launch levels



Entry Descent and Landing (EDL)

- ◆ **Concept:** Utilize excess propellant to provide electrical power from Mars orbit insertion through descent, landing, and start-up of primary surface power system
- ◆ **Application Power Level:** ~34 kW
- ◆ **Future activities:** Laboratory evaluation of pre-prototype sub-scale fuel cell stack operating on O_2/CH_4





COMMODITY GENERATION

- Feedstock Material
- + Electrical Power
- + Electrochemical Reaction
- Useful Products for other processes

Commodity Generation: Oxygen



Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)

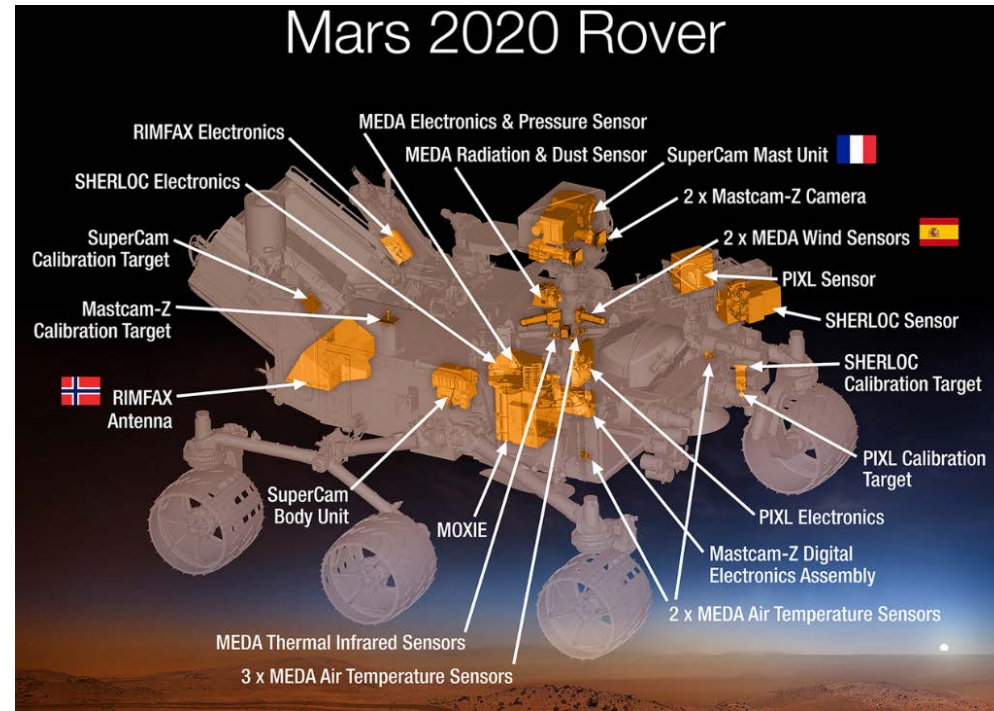
- Flight demonstration experiment as a part of the Mars 2020 rover mission
- Generates gO_2 from CO_2 in Mars atmosphere (~1% scale) using Solid Oxide Electrolysis (SOE)
- Proof-of-concept for generating propellant oxygen for Mars Ascent Vehicle (MAV) or breathing oxygen for astronauts

Oxygen Generator Assembly (OGA)

- ECLSS recovers ~ 90% of all water
- Existing technology on-board the ISS since 2008
- Advancing towards a smaller and lighter-weight version for scheduled upgrade in FY21
- Hazard evaluation testing at WSTF

Flight-qualified High Pressure electrolysis

- ECLSS systems to generate 3,000 psi gO_2 by FY24
- Evaluating existing system modifications to maintain mass while increasing generation pressure
- Investigations into conserving gH_2 by-product





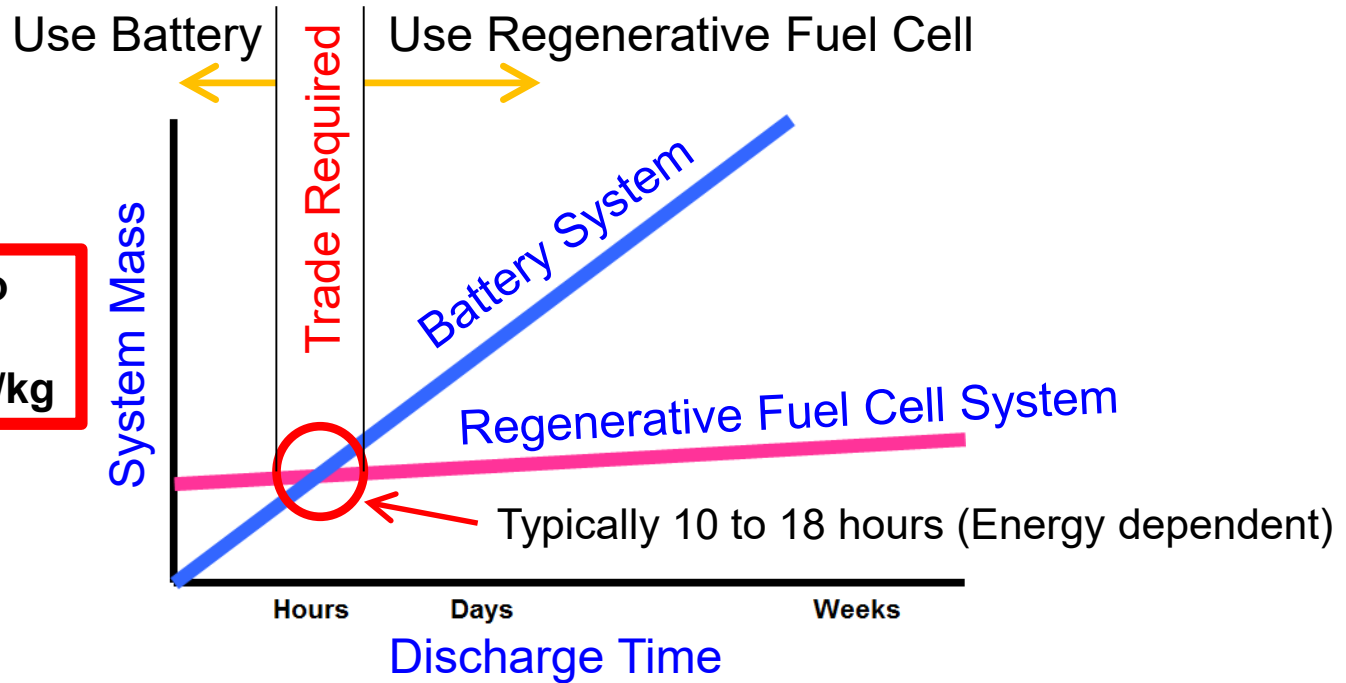
ENERGY STORAGE

- Fuel Cell System
- + Electrolyzer System
- + Interconnecting Fluidic System
- Regenerative Fuel Cell



Energy Storage: Battery vs. RFC

**Estimated cost to Lunar Surface:
\$1.5 M/kg to \$1.8 M/kg**



Energy Storage Options for 300 W_{ele} Lunar Surface System By Location

Lunar Site	Shaded Period	Energy Storage	Li-ion Mass	LRFC Mass	\$ Savings @ \$1.5 M/kg
	hours	kW•hrs	kg	kg	\$M
South Pole	73	22	<u>137</u>	<u>40</u>	\$145.5
Equator	356	107	<u>668</u>	<u>194</u>	\$711
Lacus Mortis (45° N)	362	109	<u>679</u>	<u>197</u>	\$723

Energy Storage: Regenerative Fuel Cell Trade Studies



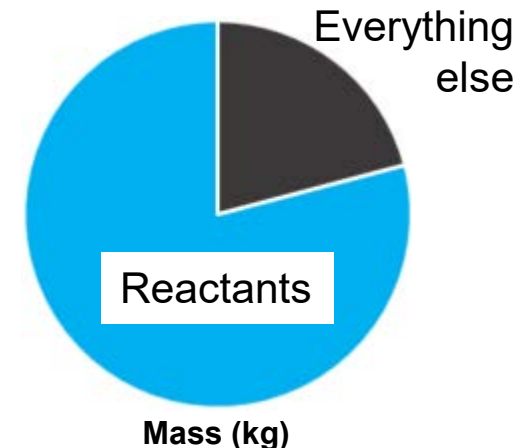
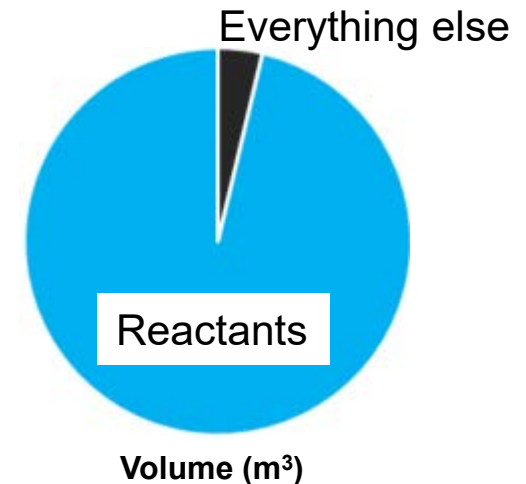
Regenerative Fuel Cell (RFC) Model

- Developed detailed RFC integrated system model to conduct sensitivity studies and mission trades
- Conducted parameter sensitivity study
 - Location primary parameter
 - Round-trip efficiency dominant metric
- Compared Solid Oxide and PEM chemistries
 - SOE not feasible for high pressure gas storage
 - SOFC limits electrical slew if sole power source
- Rotating components fail at a higher rate than electrochemical hardware

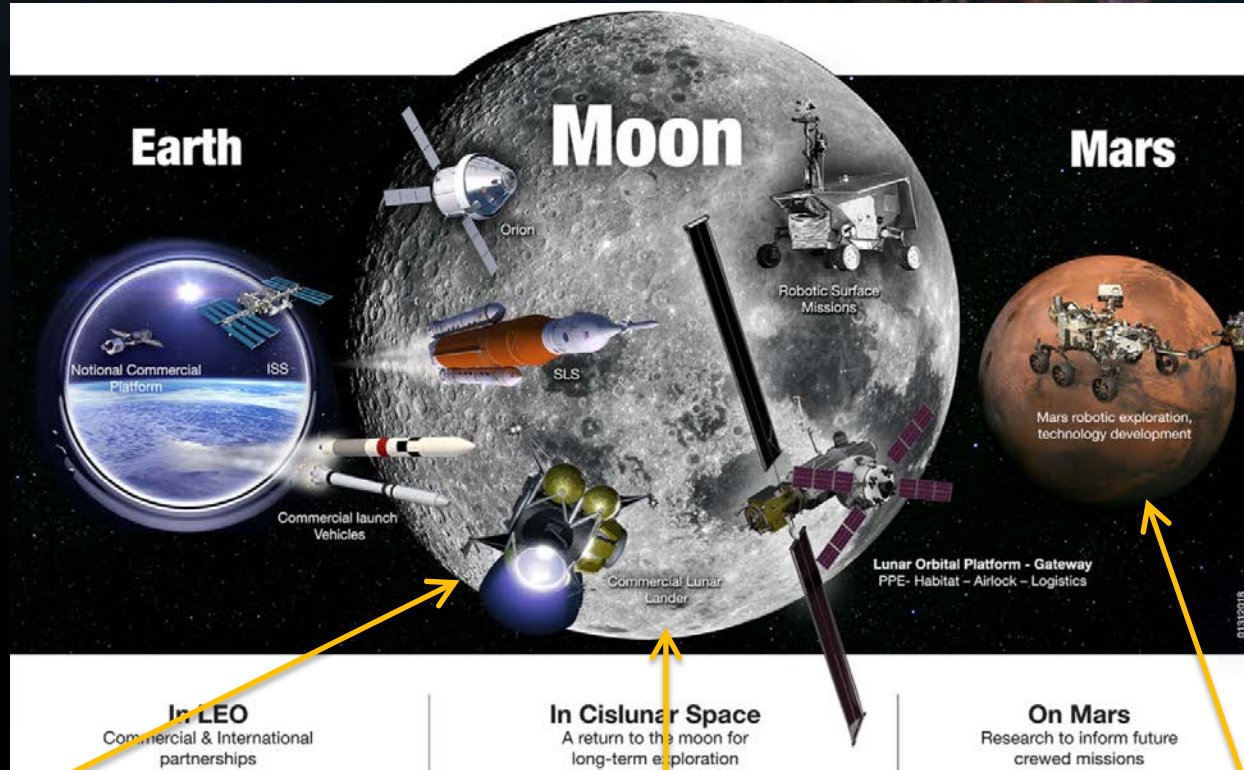
Crewed Surface Outpost Trade Study Results

- System development at low TRL
- Location determines required energy storage which sizes RFC
- PEM-based RFC near-term solution for Lunar base
- Burdened² RFC could achieve up a specific energy to 510 W•hr/kg

10 kW PEM RFC Energy Storage System for Equatorial Lunar Outpost



Review



**Electrified Aircraft
Primary Power**



In LEO
Commercial & International
partnerships

In Cislunar Space
A return to the moon for
long-term exploration

On Mars
Research to inform future
crewed missions



**Landers
Primary Power**



**Lunar Outposts
Energy Storage**



**Martian Outposts and Rovers
Primary Power
Energy Storage
Commodity Generation**



Questions?





NASA's Strategic Vision



REACH
— NEW —
HEIGHTS



REVEAL
— THE —
UNKNOWN



BENEFIT
— ALL —
HUMANKIND

www.nasa.gov



BACK-UP SLIDES

Summary of Applicable Electrochemical Chemistries



	Low Temperature		Moderate Temperature		High Temperature	
Cell Type	Proton Exchange Membrane (PEM)	Alkaline (AFC)	Alkaline (AFC)	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Electrolyte	Ionic Polymer Membrane	Anionic Polymer Membrane	KOH in asbestos matrix	Phosphoric Acid in SiC structure	Liquid carbonate in LiAlO ₂ structure	Anionic Conducting Ceramic
Operating Temperature	10 – 80 ° C	20 – 70 ° C	70 – 225 ° C	200 – 250 ° C	~650 ° C	600 – 1,000 ° C
Charge Carrier	H ⁺	OH ⁻	OH ⁻	H ⁺	CO ₃ ²⁻	O ²⁻
Load Slew Rate Capability	Very High (> 1k's mA/cm ² /s)	High (~ 1k's mA/cm ² /s)	High (~ 1k's mA/cm ² /s)	High (~ 1k's mA/cm ² /s)	Low to Medium (~100's mA/cm ² /s)	Low (~10's mA/cm ² /s)
Fuel	Pure H ₂		Pure H ₂		H ₂ , CO, Short Hydrocarbons	
Product Water Cavity	Oxygen	Hydrogen	Hydrogen	Oxygen	Hydrogen	
Product Water	Liquid Product		Operation defines product water state		Vapor, externally separated	
CO Tolerance	< 2 ppm	< 2 ppm	< 5 ppm	< 50 ppm	Fuel	
Reformer Complexity	Very High	High	High		Minimal	
Aerospace Viability	Promising	TBR (Low TRL)	No longer in production	Not Viable	Not Viable	Promising
Terrestrial Availability	High (Increasing)	Developmental (Increasing)	N/A	Moderate (Stable)	Moderate (Increasing)	High (Increasing)
Terrestrial Markets	Transportation, Logistics, Stationary Power (C, I, & R)		N/A	Stationary Power (C)	Co-generation and Stationary Power (C & I)	Co-generation and Stationary Power (C, I, & R)

C = Commercial
I = Industrial
R = Residential

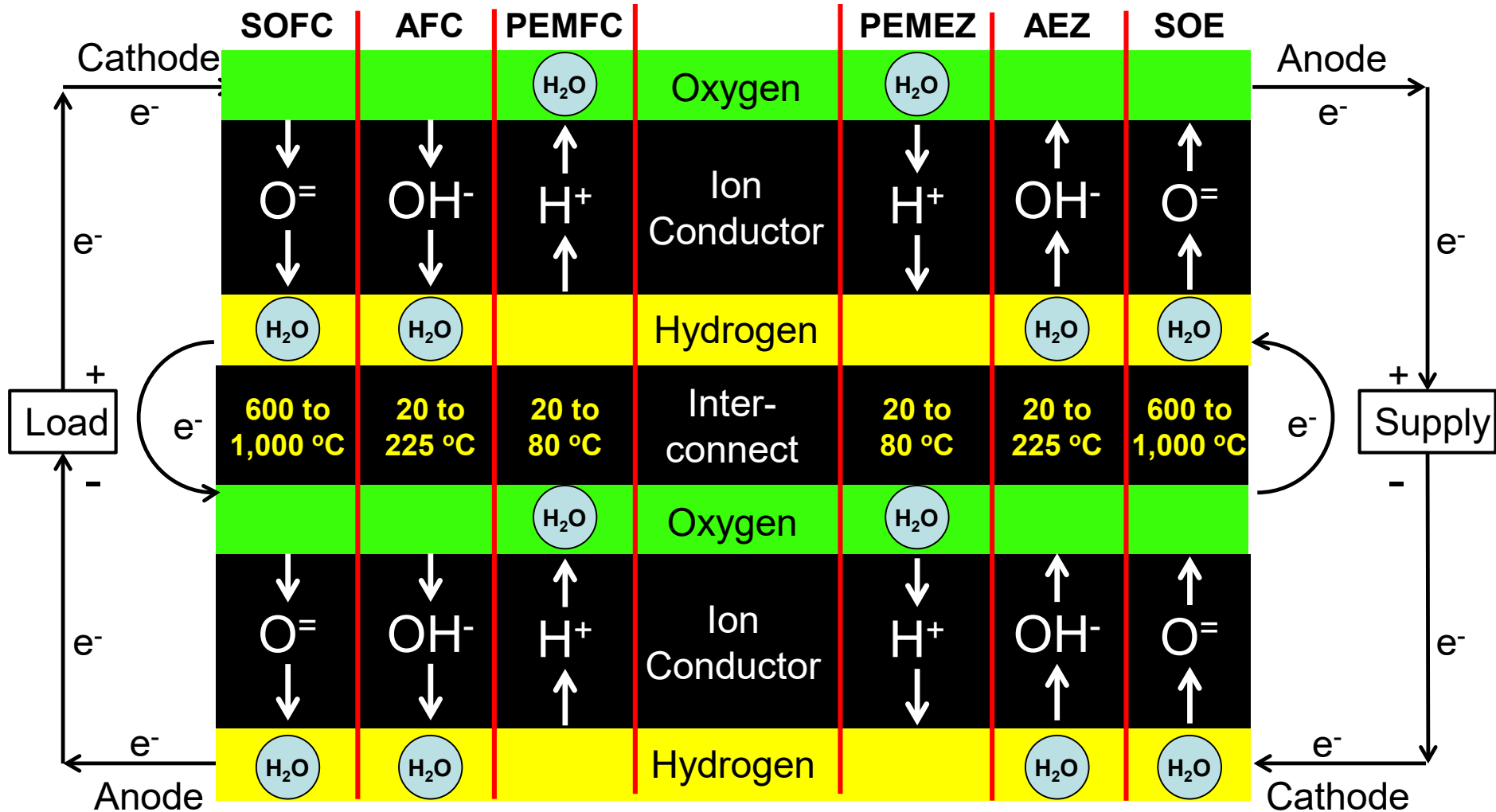


Electrochemical Reactions

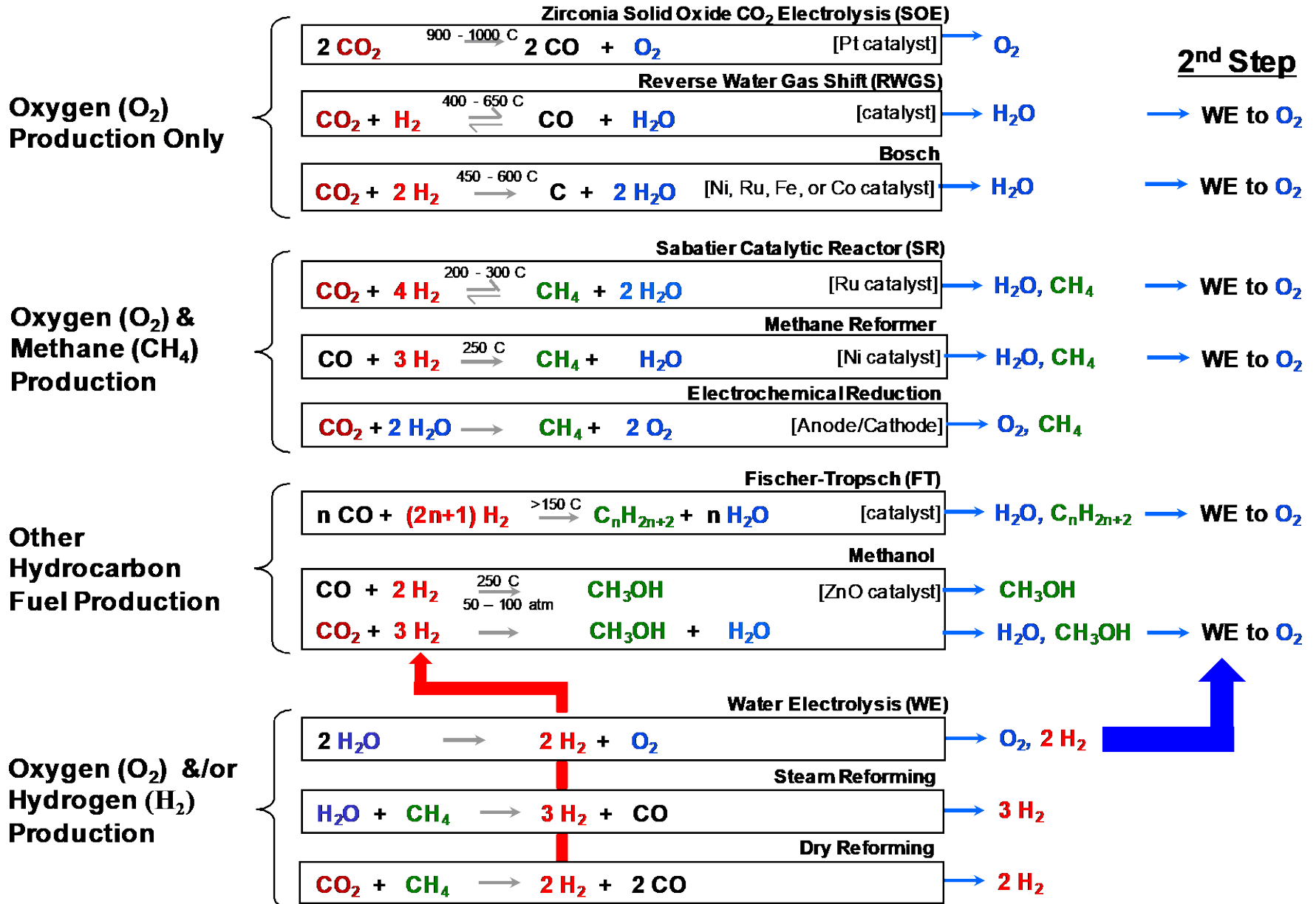
Recombination

Fuel Cell Reaction

Electrolysis



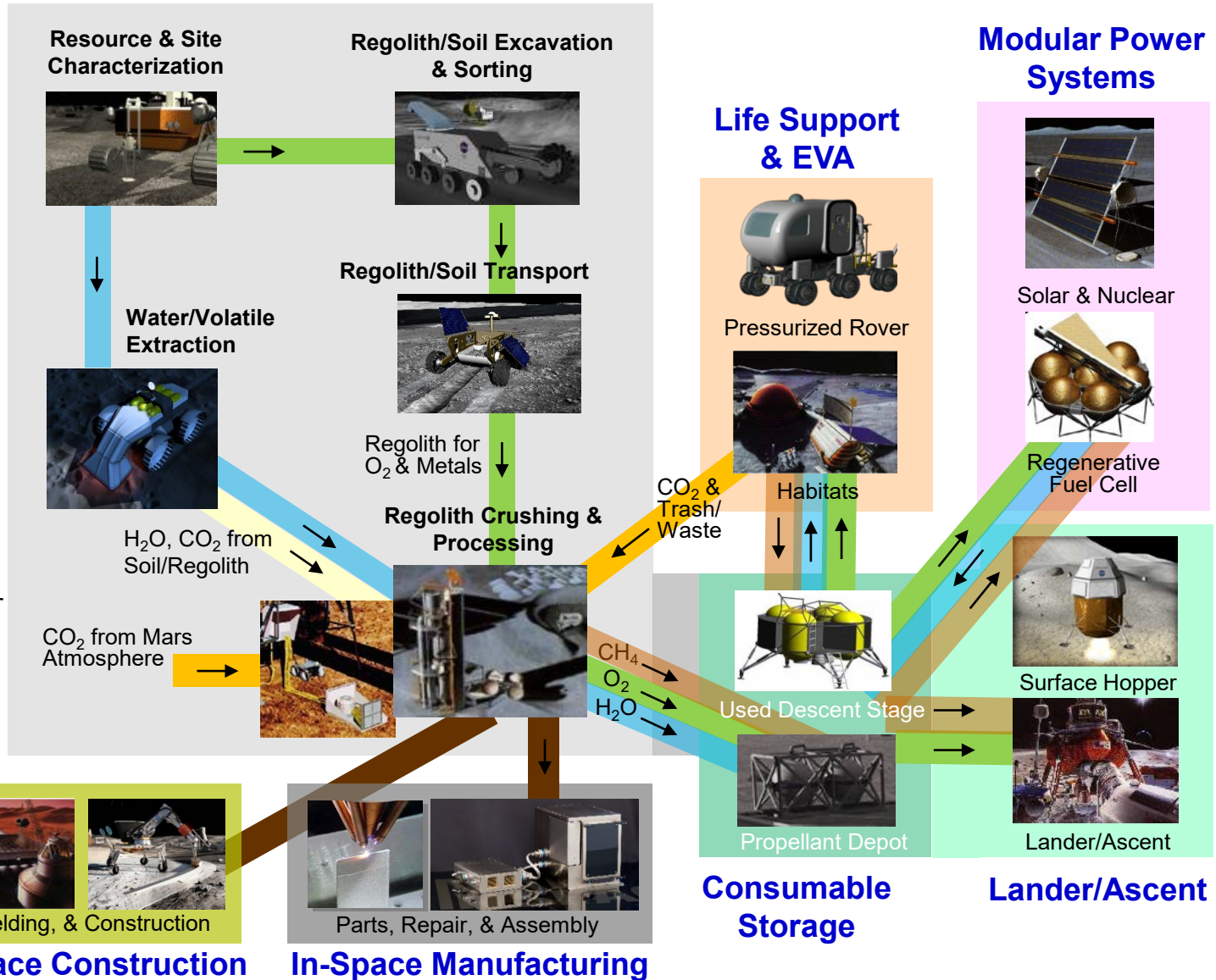
The Chemistry of Mars ISRU



Energy Storage Integrated with Exploration Elements



ISRU Resources & Processing



Modular Power Functions/ Elements

- Power Generation
- Power Distribution
- Energy Storage (O₂ & H₂)

Support Functions /Elements

- ISRU
- Life Support & EVA
- O₂, H₂, and CH₄ Storage and Transfer

Shared Hardware to Reduce Mass & Cost

- Solar arrays/nuclear reactor
- Water Electrolysis
- Reactant Storage
- Cryogenic Storage
- Mobility