Fuel Cell Research and Development for Earth and Space Applications

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Department of Energy
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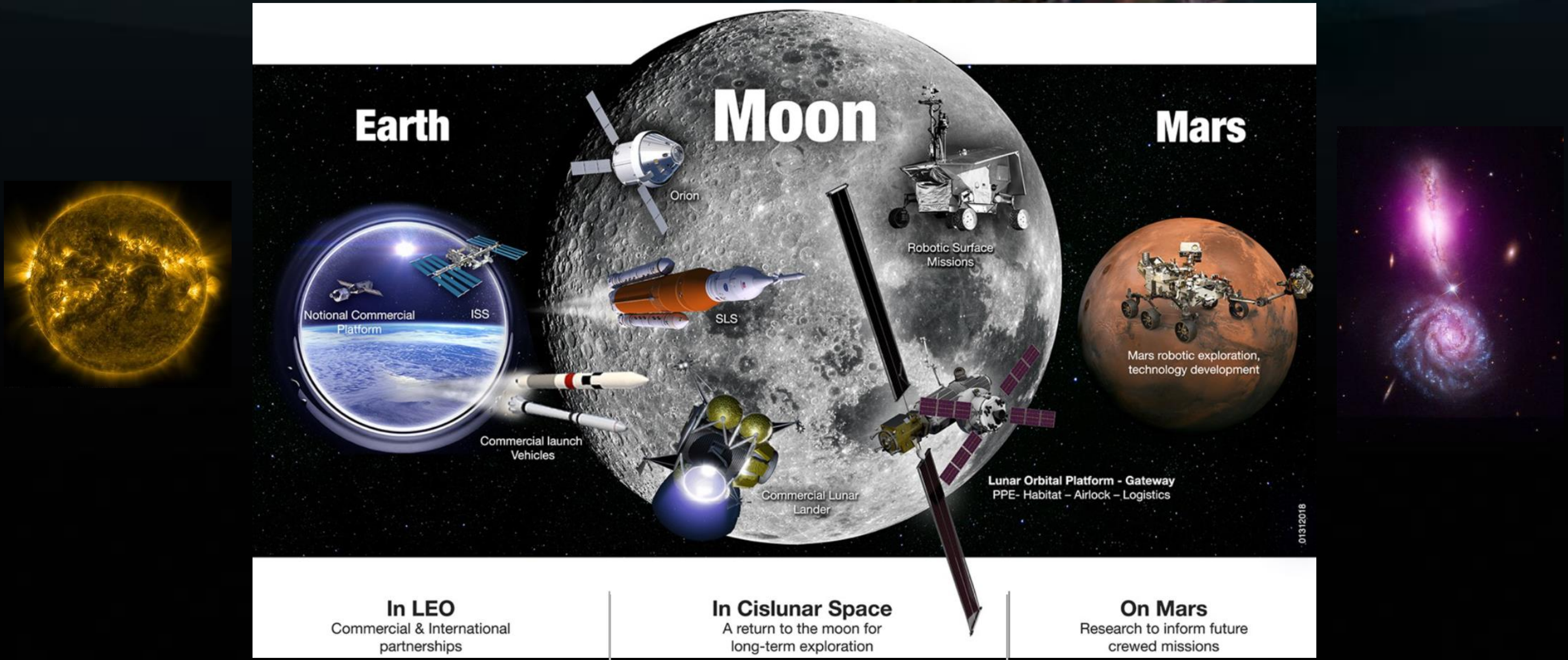
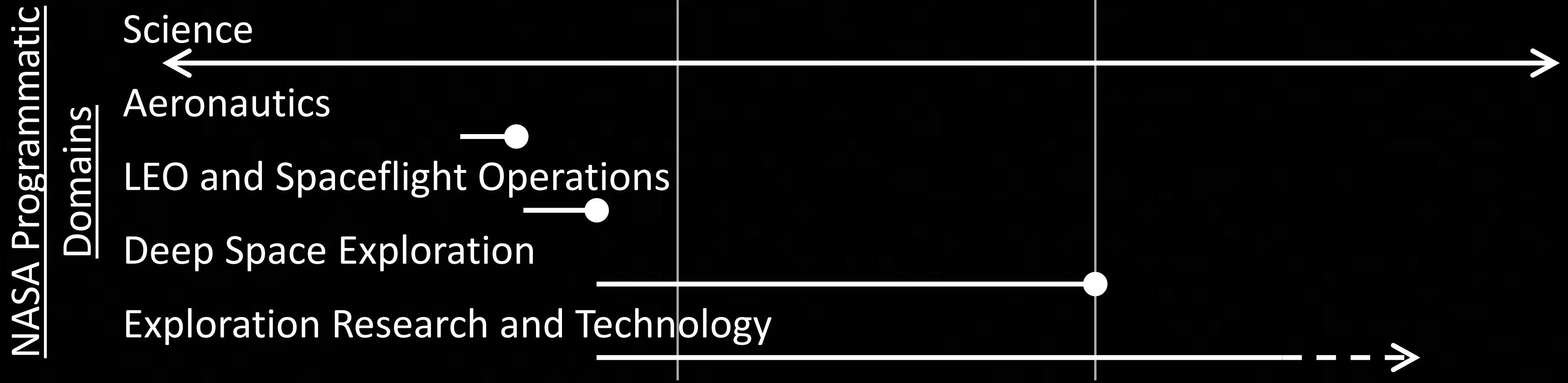
Presentation Outline

- 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

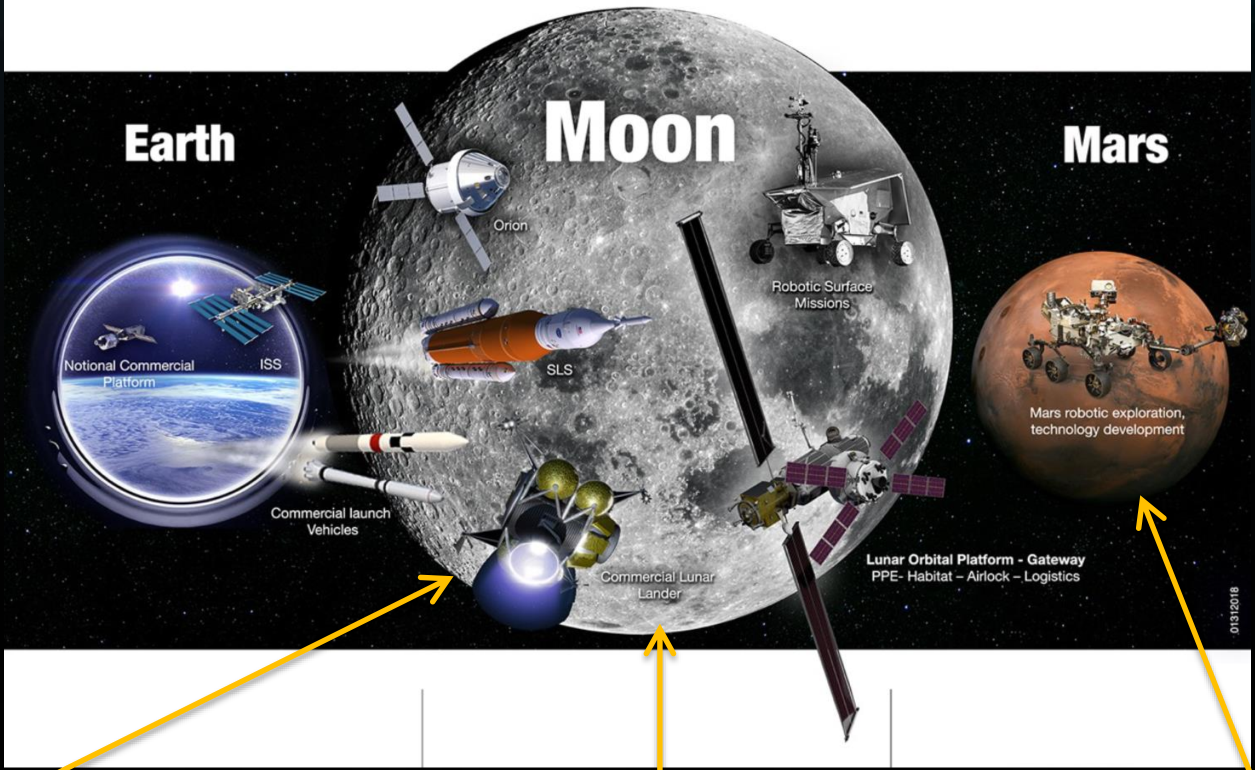




NASA Programmatic Domains

- 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:

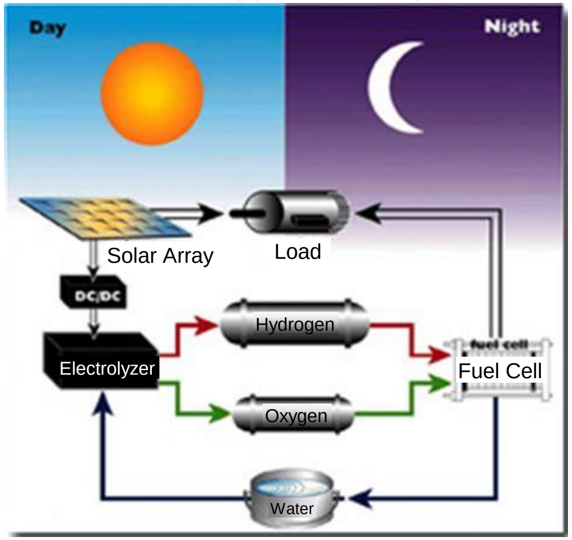
Sustained High-Power

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

Regenerative Fuel Cell

Energy Storage

Charging



Discharging

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

$$2\ H_2O \xrightarrow{⚡} 2\ H_2 + O_2$$

or

$$2\ CO_2 \xrightarrow{⚡} 2\ CO + O_2$$

Description

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

NASA Applications:

Life-support, ISRU

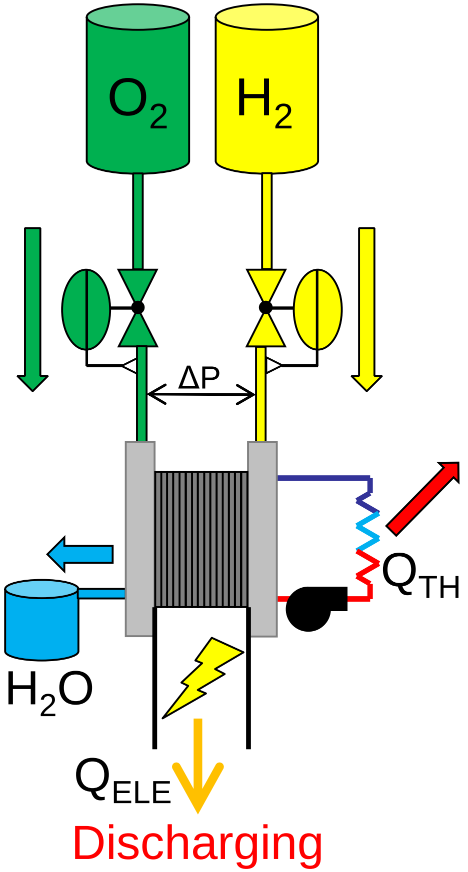
- Oxygen Generation
- Propellant Generation
- Material Processing

Definitions:
Types of Aerospace Fuel Cell Systems

Fuel Cell

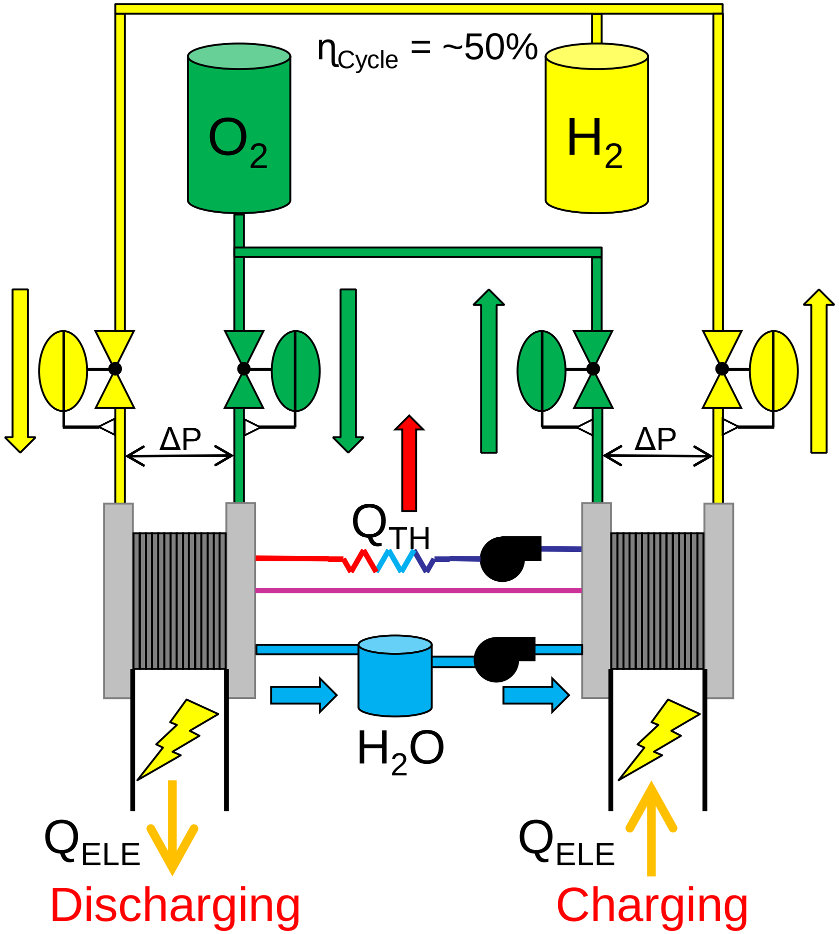
Power Generation

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



Regenerative Fuel Cell

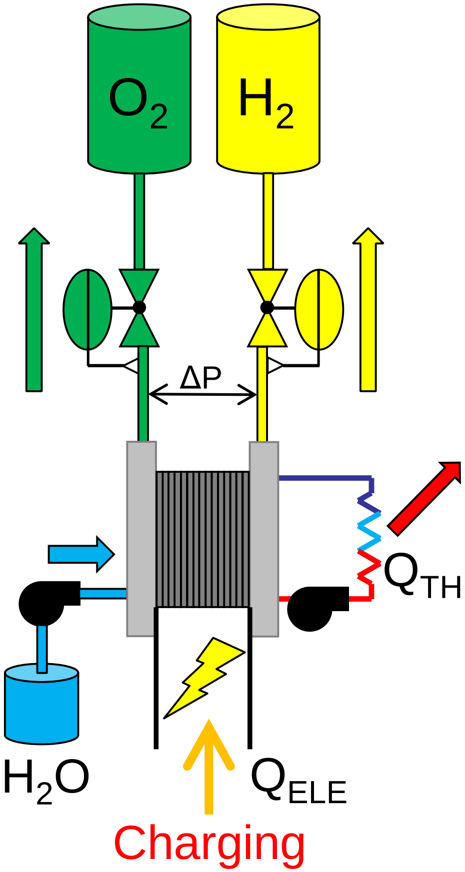
Energy Storage



Electrolysis

Commodity Generation

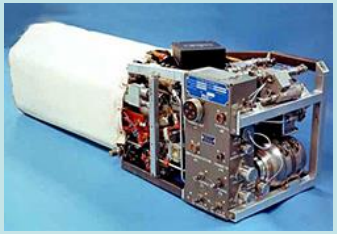
$2H_2O + 4e^- \rightarrow 2H_2 + O_2 + Heat$



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

Comparison of Fuel Cell Technologies

Aerospace



Space Shuttle Fuel Cell Stack

(1979 - 2014)

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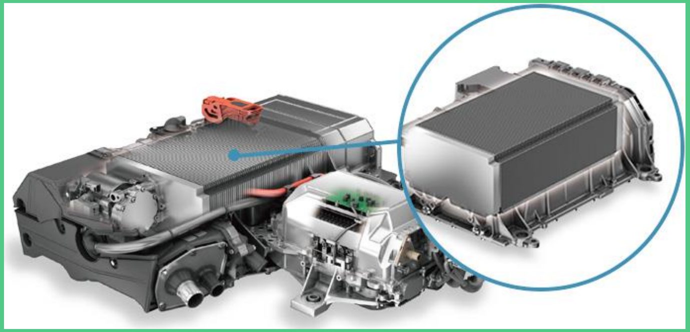
Terrestrial



Toyota Mirai Fuel Cell[1]

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

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

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, μg
Reactant Storage and Management	Fluidic Components	8+	Moderate	O_2 vs air
	Procedures	5	Moderate	O_2 vs air, Performance
	Thermal	8+	Moderate	μg, Vacuum
	Materials	8+	Low	O_2 vs air
	Water Management	5+	Low	O_2 vs air, μg
FC / EZ / RFC System Avionics	Hardware/PCB	8+	High	
	Power Management	8+	High	
	Structure	8+	High	
	Thermal	8+	High	
	Instrumentation	8+	Moderate	

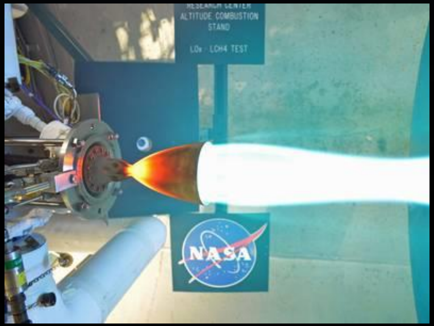
NOTE: Not all relevant technologies exist within the same application. Elements of multiple terrestrial applications are required to meet various NASA mission requirements.

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

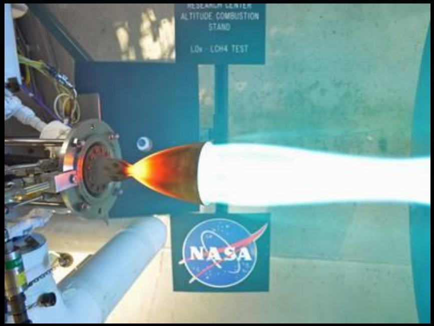
- Lunar Surface Systems
- Lunar Landers / Rovers
- HALE Un-crewed Aerial Systems (UAS)

NASA Applications researching Electrochemical Systems

Power Generation: Fuel Cells

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

Commodity Generation: Electrolysis



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Energy Storage: Regenerative Fuel Cell

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

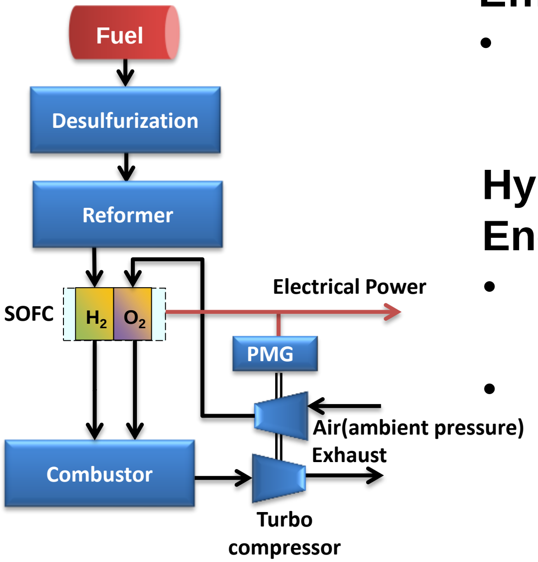
Legend
- ➢ Hardware Development
- ❖ Analytical Development
- • Recent work not funded this Fiscal Year

POWER GENERATION

Oxidizer
+ Fuel
+ Electrochemical Reaction
Electrical Power

Power Generation: Fuel Cells
Electrification of Aircraft

- 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



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

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

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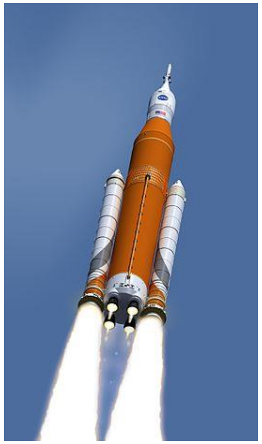
Power Generation: Fuel Cell Analytical Activities

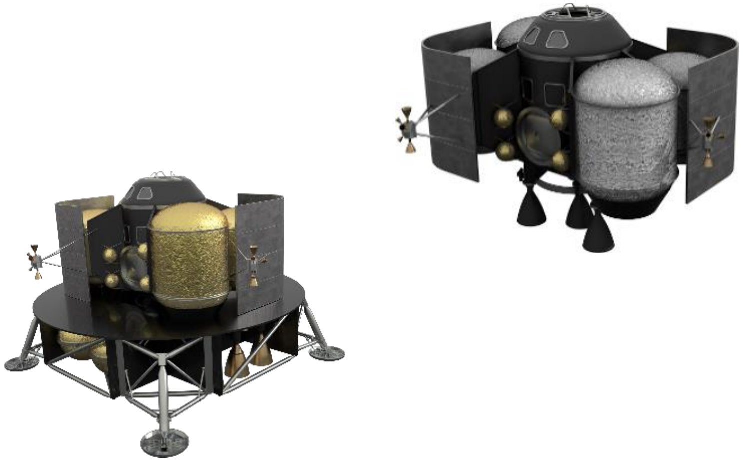
High Power Fuel Cells

- **Concept: Crewed transit vehicles, crewed rovers, or rovers with energy-intense 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**

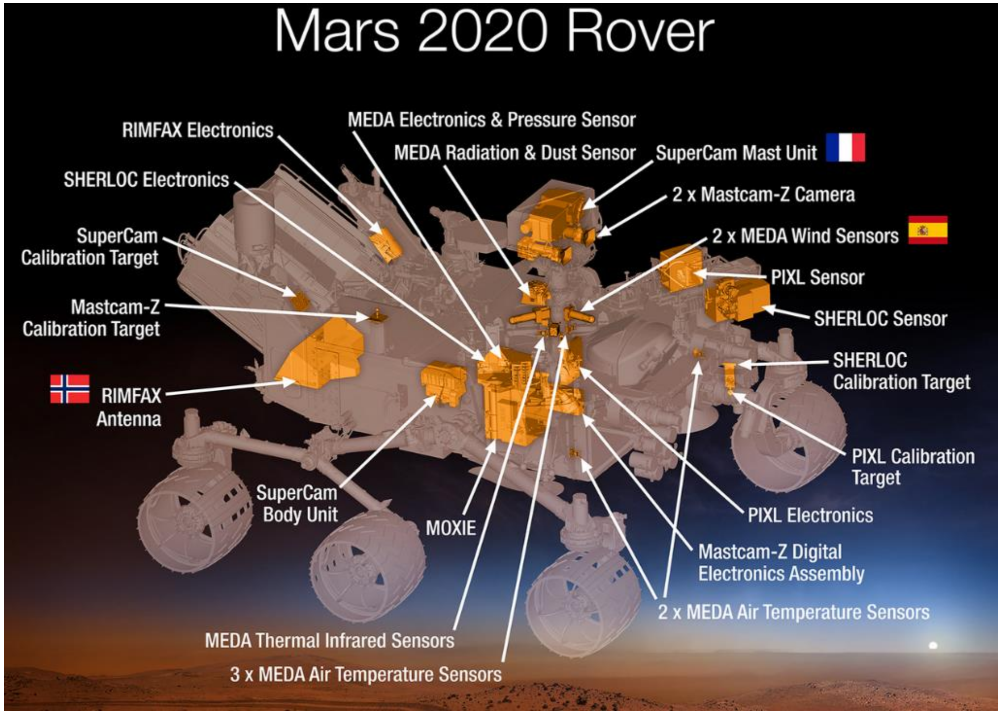


COMMODITY GENERATION

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**



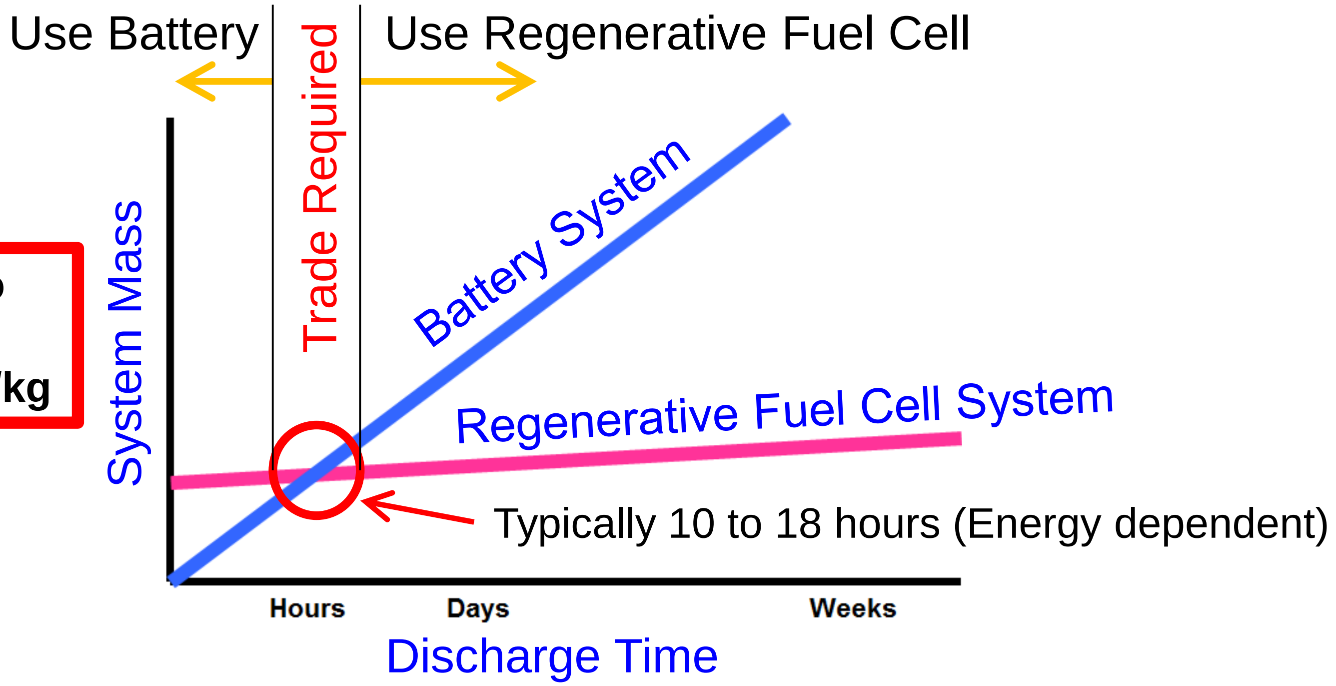
- **Oxygen Generator Assembly (OGA)**
  - **ECLSS recovers ~ 90% of all water**
  - **Existing technology on-board the ISS since 2008**
  - **Advancing towards a smaller and lighter-weight version for scheduled upgrade in FY21**
  - **Hazard evaluation testing at WSTF**

- **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
<u>+ Interconnecting Fluidic System</u>
Regenerative Fuel Cell

Energy Storage: Battery vs. RFC



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

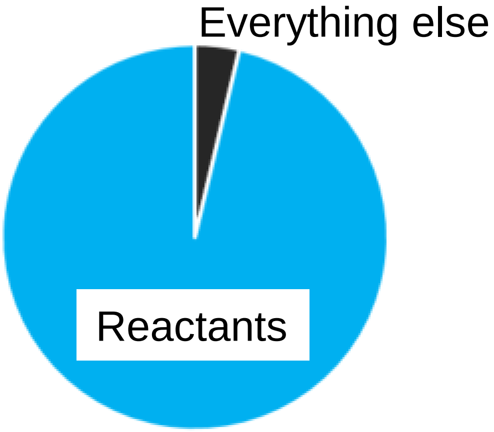
Energy Storage Options for 300 W_{ele} Lunar Surface System By Location

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	**137**	**40**	**$145.5**
Equator	356	107	**668**	**194**	**$711**
Lacus Mortis (45° N)	362	109	**679**	**197**	**$723**

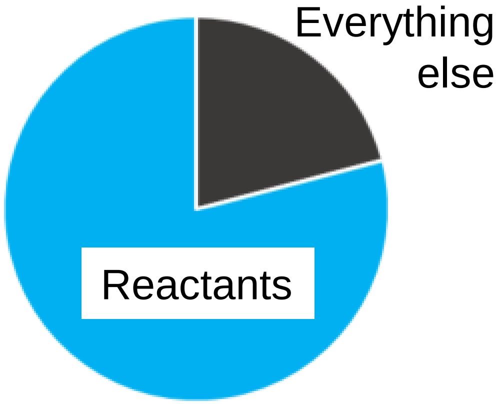
Energy Storage:
Regenerative Fuel Cell Trade Studies

- **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
  - Burdened[2] RFC could achieve up a specific energy to 510 W•hr/kg

<u>10 kW PEM RFC Energy Storage System for Equatorial Lunar Outpost</u>

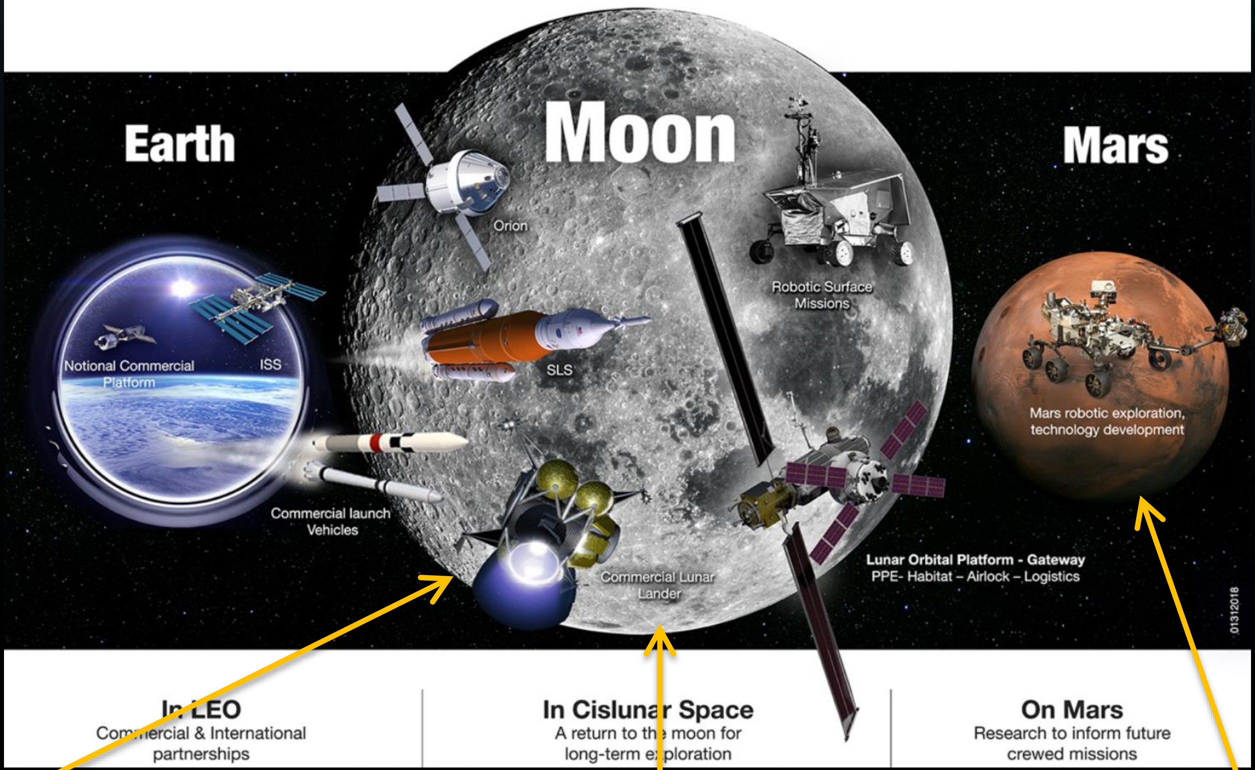


Volume (m^3)



Mass (kg)

Review



Electrified Aircraft
Primary Power

Landers
Primary Power

Lunar Outposts
Energy Storage

Martian Outposts and Rovers
Primary Power
Energy Storage
Commodity Generation

Questions?


REACH
NEW
HEIGHTS
REVEAL
THE
UNKNOWN
BENEFIT
ALL
HUMANKIND

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BACK-UP SLIDES

Summary of Applicable Electrochemical Chemistries

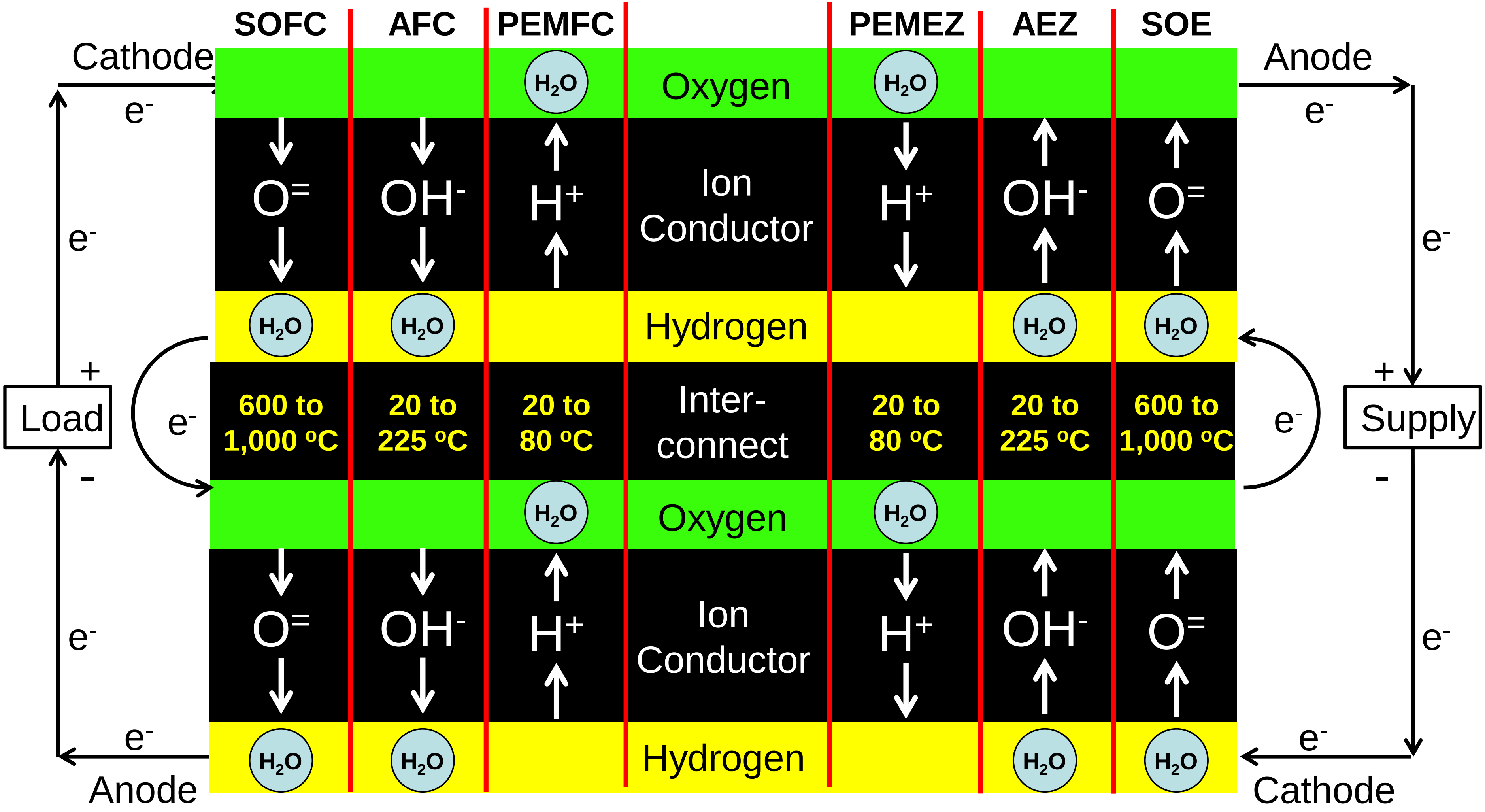
	Low Temperature		Moderate Temperature		High Temperature	
Cell Type	Proton Exchange Membrane (PEM)	Alkaline (AFC)	Alkaline (AFC)	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Electrolyte	Ionic Polymer Membrane	Anionic Polymer Membrane	KOH in asbestos matrix	Phosphoric Acid in SiC structure	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 C = Commercial I = Industrial R = Residential	Transportation, Logistics, Stationary Power (C, I, & R)	Transportation, Logistics (C)	N/A	Stationary Power (C)	Co-generation and Stationary Power (C & I)	Co-generation and Stationary Power (C, I, & R)

Electrochemical Reactions

Recombination

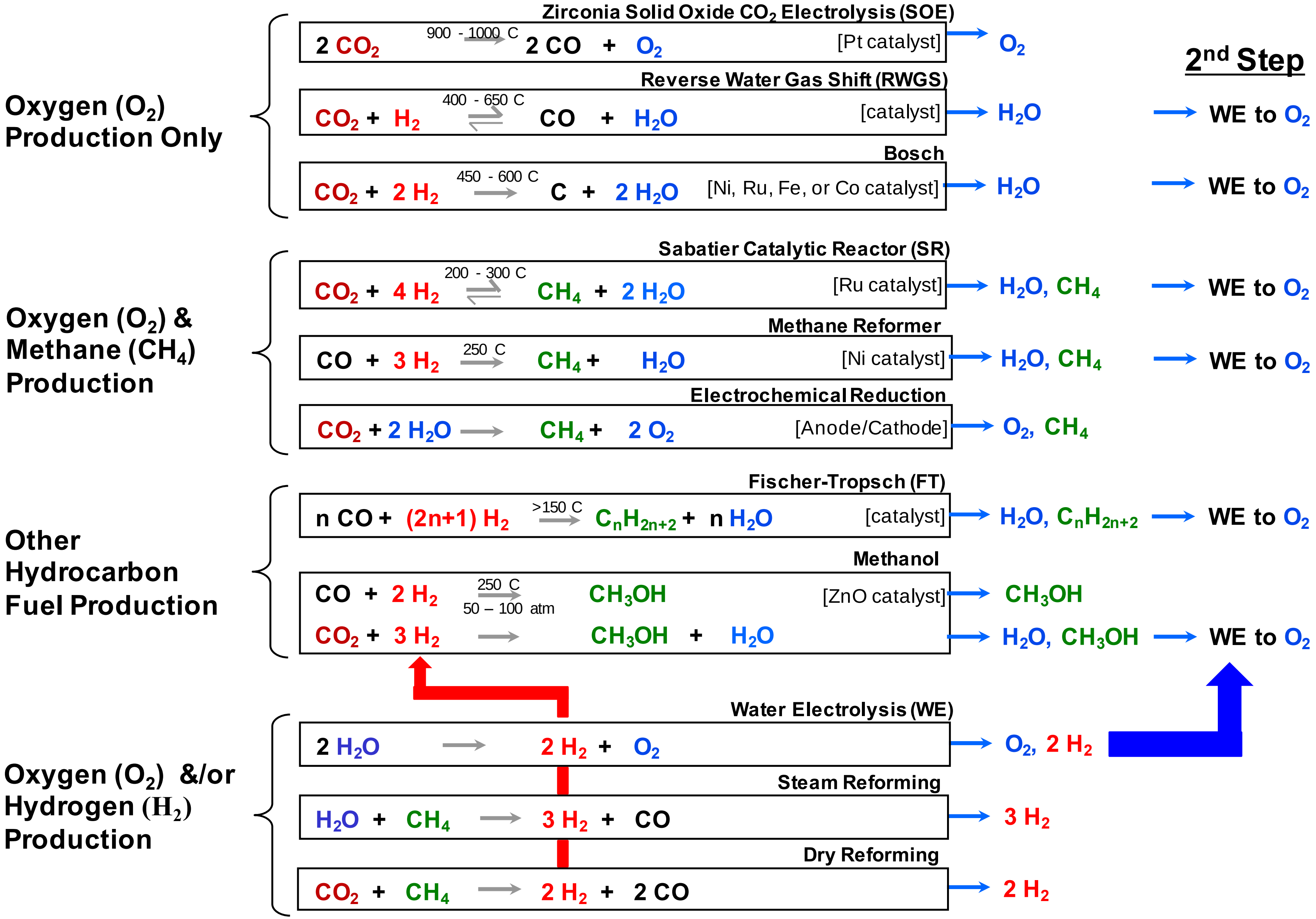
Fuel Cell Reaction

Electrolysis



SOFC	AFC	PEMFC		PEMEZ	AEZ	SOE
		H_2O	Oxygen	H_2O		
↓ $O^=$ ↓	↓ OH^- ↓	↑ H^+ ↑	Ion Conductor	↓ H^+ ↓	↑ OH^- ↑	↑ $O^=$ ↑
H_2O	H_2O		Hydrogen		H_2O	H_2O
600 to 1,000 °C	20 to 225 °C	20 to 80 °C	Inter-connect	20 to 80 °C	20 to 225 °C	600 to 1,000 °C
		H_2O	Oxygen	H_2O		
↓ $O^=$ ↓	↓ OH^- ↓	↑ H^+ ↑	Ion Conductor	↓ H^+ ↓	↑ OH^- ↑	↑ $O^=$ ↑
H_2O	H_2O		Hydrogen		H_2O	H_2O

The Chemistry of Mars ISRU



2nd Step

Oxygen (O_2) Production Only

Zirconia Solid Oxide CO_2 Electrolysis (SOE)
$2\ CO_2 \xrightarrow{900-1000\ C} 2\ CO + O_2$ [Pt catalyst] → O_2

Reverse Water Gas Shift (RWGS)
$CO_2 + H_2 \overset{400-650\ C}{\rightleftharpoons} CO + H_2O$ [catalyst] → H_2O → WE to O_2

Bosch
$CO_2 + 2\ H_2 \xrightarrow{450-600\ C} C + 2\ H_2O$ [Ni, Ru, Fe, or Co catalyst] → H_2O → WE to O_2

Oxygen (O_2) & Methane (CH_4) Production

Sabatier Catalytic Reactor (SR)
$CO_2 + 4\ H_2 \overset{200-300\ C}{\rightleftharpoons} CH_4 + 2\ H_2O$ [Ru catalyst] → H_2O, CH_4 → WE to O_2

Methane Reformer
$CO + 3\ H_2 \xrightarrow{250\ C} CH_4 + H_2O$ [Ni catalyst] → H_2O, CH_4 → WE to O_2

Electrochemical Reduction
$CO_2 + 2\ H_2O \longrightarrow CH_4 + 2\ O_2$ [Anode/Cathode] → O_2, CH_4

Other Hydrocarbon Fuel Production

Fischer-Tropsch (FT)
$n\ CO + (2n+1)\ H_2 \xrightarrow{>150\ C} C_nH_{2n+2} + n\ H_2O$ [catalyst] → H_2O, C_nH_{2n+2} → WE to O_2

Methanol
$CO + 2\ H_2 \xrightarrow[50-100\ atm]{250\ C} CH_3OH$ [ZnO catalyst] → CH_3OH
$CO_2 + 3\ H_2 \longrightarrow CH_3OH + H_2O$ → H_2O, CH_3OH → WE to O_2

Oxygen (O_2) &/or Hydrogen (H_2) Production

Water Electrolysis (WE)
$2\ H_2O \longrightarrow 2\ H_2 + O_2$ → O_2, $2\ H_2$

Steam Reforming
$H_2O + CH_4 \longrightarrow 3\ H_2 + CO$ → $3\ H_2$

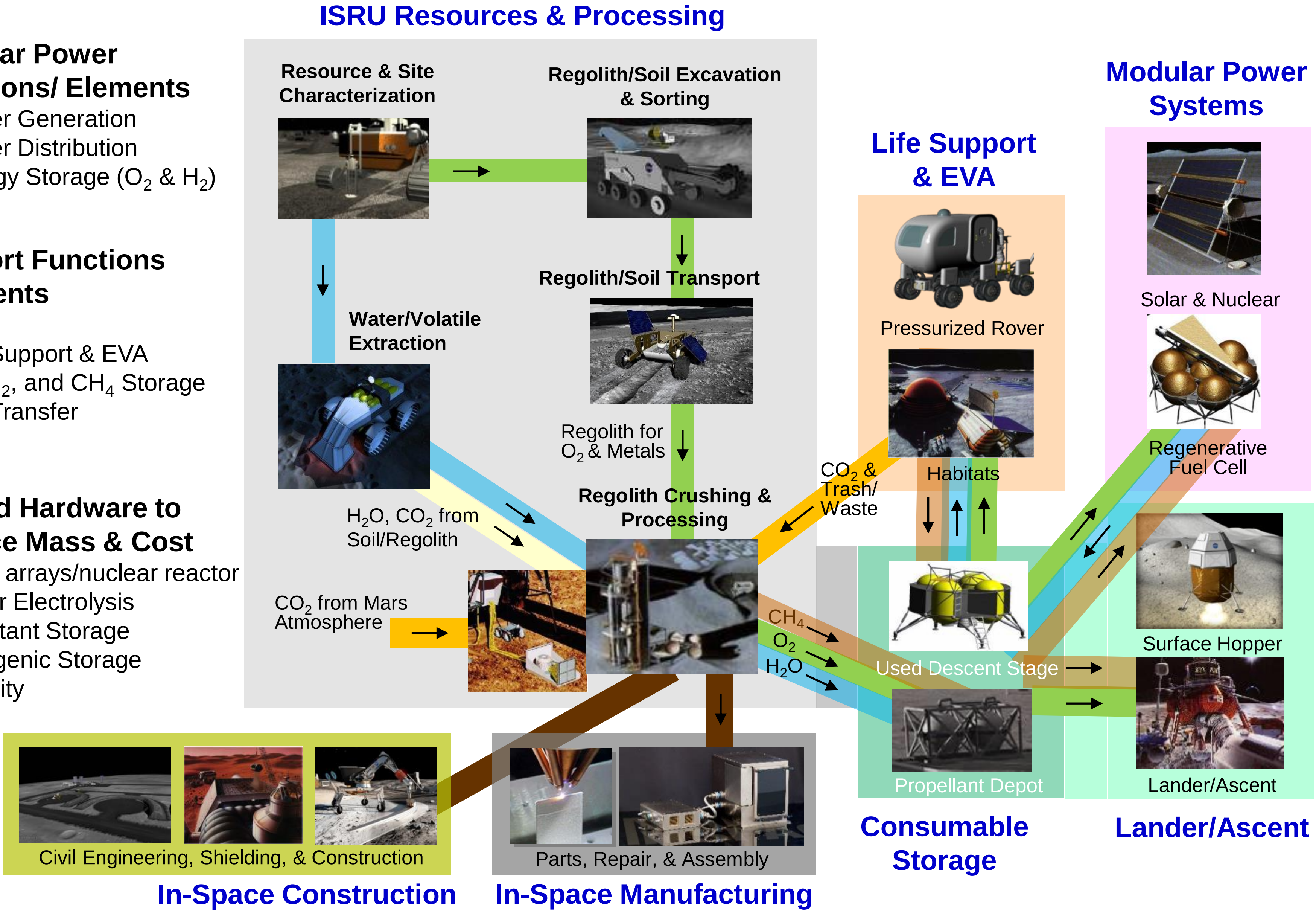
Dry Reforming
$CO_2 + CH_4 \longrightarrow 2\ H_2 + 2\ CO$ → $2\ H_2$

Energy Storage Integrated with Exploration Elements

Modular Power Functions/ Elements
- Power Generation
- Power Distribution
- Energy Storage (O_2 & H_2)

Support Functions /Elements
- ISRU
- Life Support & EVA
- O_2, H_2, and CH_4 Storage and Transfer

Shared Hardware to Reduce Mass & Cost
- Solar arrays/nuclear reactor
- Water Electrolysis
- Reactant Storage
- Cryogenic Storage
- Mobility



ISRU Resources & Processing

Resource & Site Characterization

Regolith/Soil Excavation & Sorting

Regolith/Soil Transport

Water/Volatile Extraction

Regolith for O_2 & Metals

Regolith Crushing & Processing

H_2O, CO_2 from Soil/Regolith

CO_2 from Mars Atmosphere

CO_2 & Trash/ Waste

CH_4

O_2

H_2O

Life Support & EVA

Pressurized Rover

Habitats

Modular Power Systems

Solar & Nuclear

Regenerative Fuel Cell

Used Descent Stage

Propellant Depot

Surface Hopper

Lander/Ascent

Consumable Storage

Lander/Ascent

Civil Engineering, Shielding, & Construction

Parts, Repair, & Assembly

In-Space Construction

In-Space Manufacturing