National Aeronautics and
Space Administration

Fuel Cell and Hydrogen Activities Overview

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For Robinson Research Institute visit NASA GRC
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Technology Descriptions

https://www1.grc.nasa.gov/research-and-engineering/power/

Energy Storage

Aerospace power systems require high performance energy storage technologies to operate in challenging space and aeronautic environments.

In our unique facilities at Glenn Research Center, we develop regenerative fuel cells (RFC) and aerospace batteries to support NASA missions and programs.

RFC to develop an externally-facing for public.

Electrochemical Systems for Space

Space	≠	Terrestrial

Space

Differentiating Characteristics

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

Terrestrial

Differentiating Characteristics

- Oxygen scavenged from air
- Nitrogen in air facilitates water removal

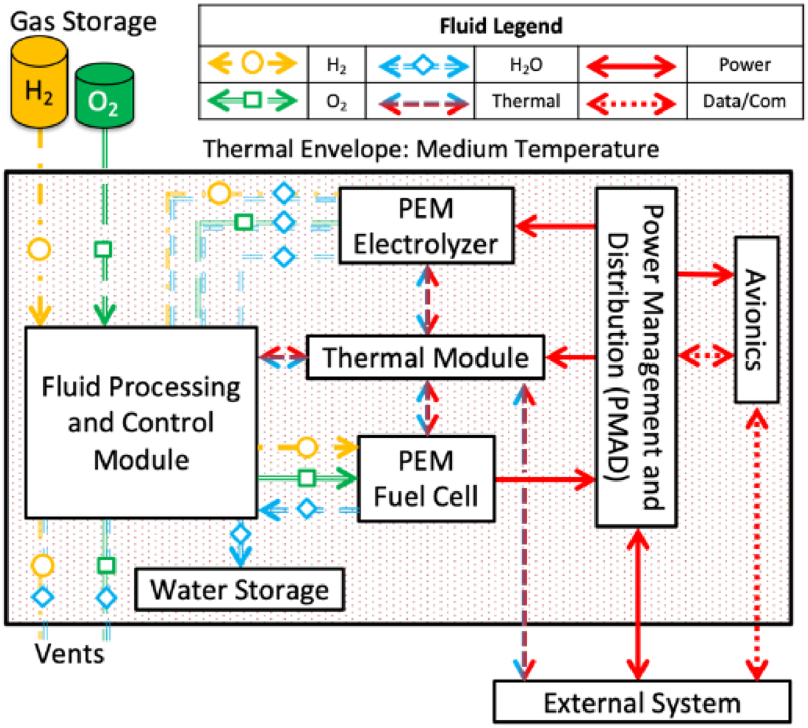
Fluid management issues and environmental conditions make aerospace and terrestrial electrochemical systems functionally dissimilar

Regenerative Fuel Cell Technology

Technology Product Capability: Develop RFC energy storage system technology that can provide sustained and reliable electrical power for lunar surface and near-surface missions where photovoltaics/battery or nuclear options may not be feasible; advance integrated RFC from TRL3 to at least TRL5 for lunar surface applications.

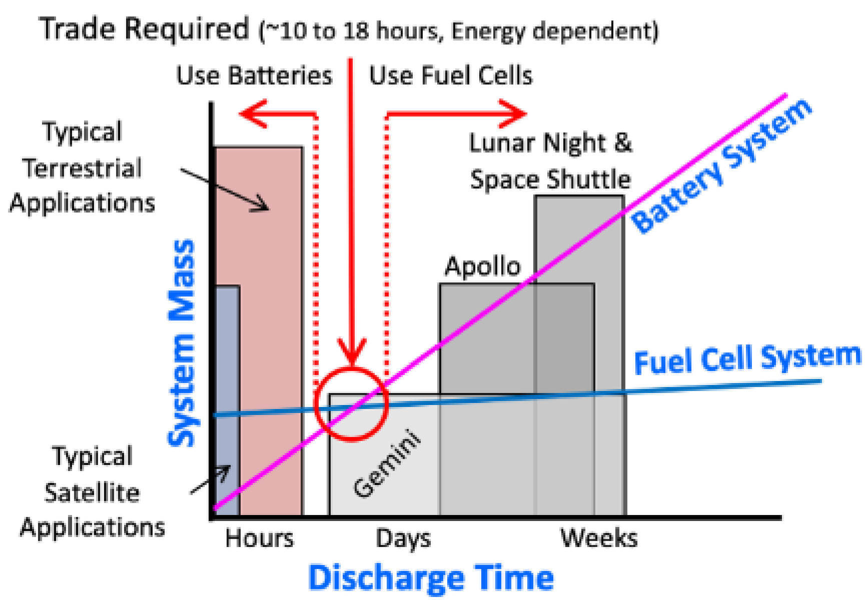
What is an RFC?

An energy storage system that utilizes hydrogen and oxygen gases to store energy.



Why?

Higher specific energy (W·hr/kg) for high energy applications where fully packaged battery systems become too massive.



Energy Options for Space Applications	Battery = TRL 9 Primary Fuel Cell = TRL 5 Regenerative Fuel Cell = TRL 3

Primary Fuel Cells vs. Primary Battery

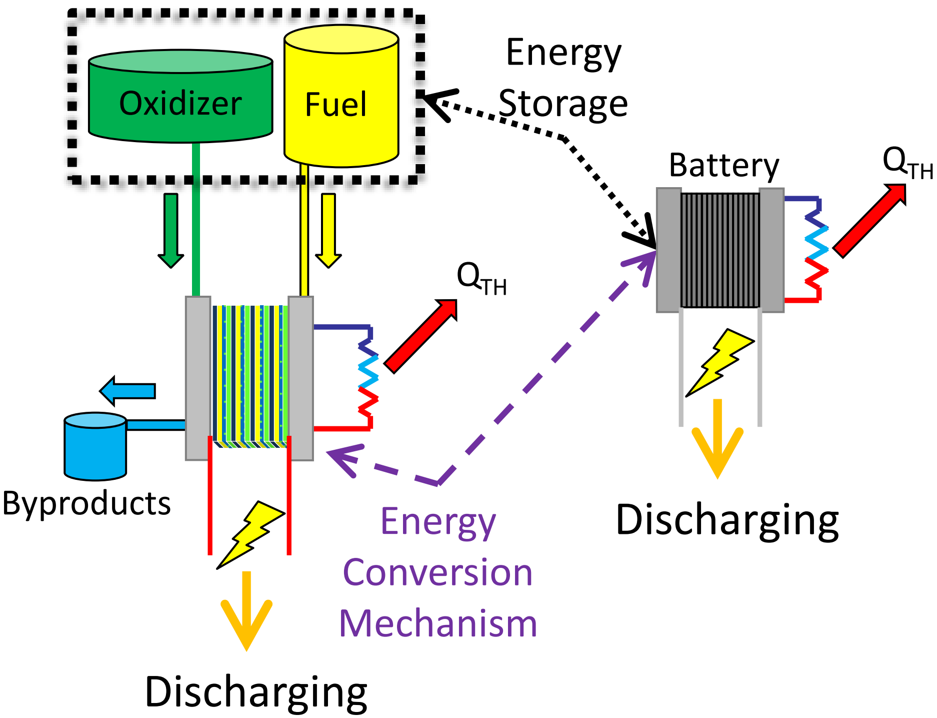
__Electrical Power__ to enable and augment exploration activities

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

Primary Fuel Cell | **Primary Battery**

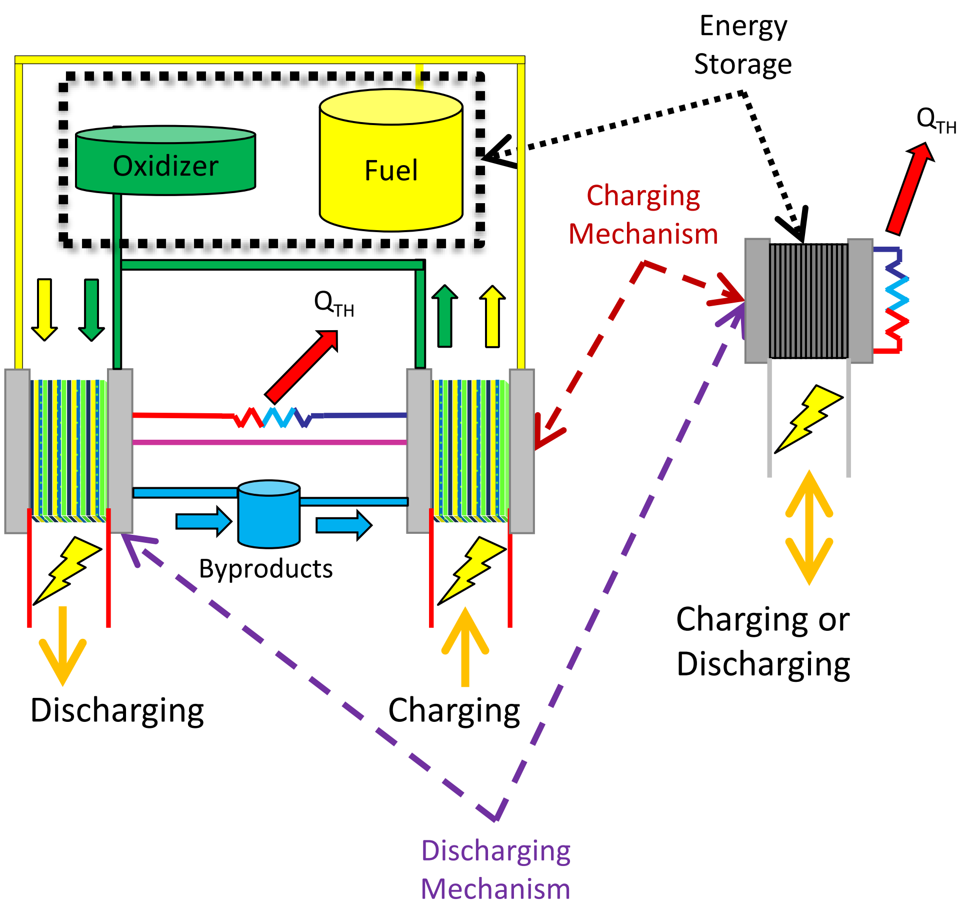


- Different Hazards and Mitigations
  - Batteries sensitive to Thermal Runaway
  - Fuel Cells sensitive to Material Compatibility and Process Fluid management issues
- Different Voltage to State-of-Charge (SoC) relationships
  - Battery voltage dependent on quantity of stored energy
  - Fuel Cell voltage 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

Regenerative Fuel Cell   Rechargeable Battery



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

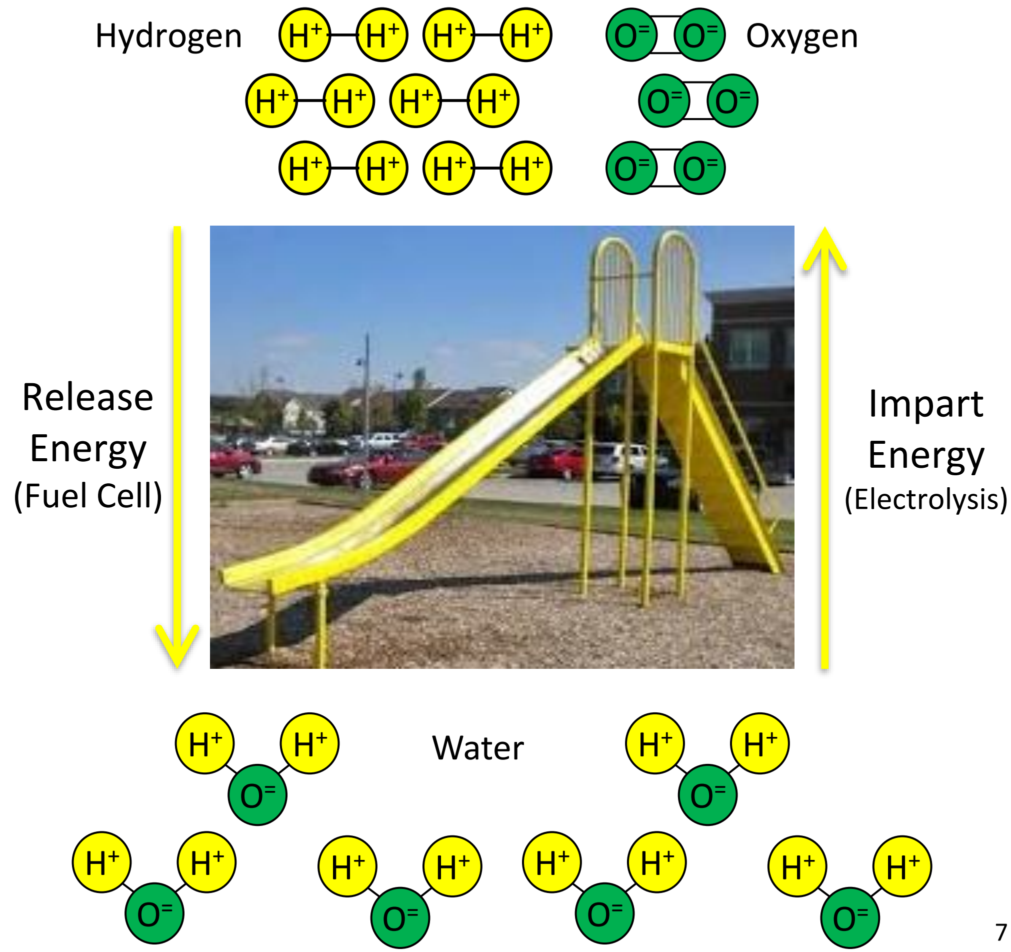
Basic Reactions

- **The Proton Exchange Membrane (PEM) technology facilitates the oxidation-reduction reactions of hydrogen, oxygen, and water**

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

- **This is a Reversible reaction:**
  - Fuel Cell reaction releases energy
  - Electrolysis reaction requires energy

- **Low temperatures and multiple inefficiencies limit cyclic or "round-trip" efficiency to < 60%**



Electrochemical System Chemistry Options

	Low Temperature		Moderate Temperature		High Temperature	
Cell Type	Proton Exchange Membrane (PEM)	Alkaline Polymer Membrane (AEM)	Alkaline	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Electrolyte (State)	Ionic Polymer Membrane (Solid)	Anionic Polymer Membrane (Solid)	KOH in Asbestos matrix (Liquid)	Phosphoric Acid in SiC matrix (Liquid)	Carbonate in $LiAlO_2$ matrix (Liquid)	Conducting Ceramic (Solid)
Maturity (Terrestrial / Aerospace)	TRL 9 / TRL 5* (* = Application-specific)	TRL 6 / TRL 3	TRL 9 / TRL 3 (N/A)	TRL 9 / TRL 3	TRL 9 / TRL 3	TRL 9 (4) / TRL 5* (* = Application-specific)
Power Applications	Base-load, Transient	Base-load, some Transient	Base-load, many Transient	Base-load, some Transient	Base-load only	Base-load only
Aerospace Viability (Development Challenges)	Very high (Awaiting μg demonstration, Balance of Plant)	TBR (Low TRL, Short life)	Moderate (N/A) (Liquid electrolyte, Ion migration, Heritage tech not available in US)	Very, very low (Liquid Electrolyte)	Very, very low (Material Compatibility, Low Specific Power)	Very high (Scale-up, Material Compatibility, Balance of Plant)
Reversibility (Fuel cell & Electrolysis modes in same cell)	Very Limited (Hydrophobic / H[illegible] Surfaces	Very Limited [illegible]	Limited	Limited	High [illegible]sure-limited)	High (Pressure-limited)
Operating Temperature	10 – 80 [illegible]	[illegible]	[illegible]	[illegible]	[illegible]650 ° C	600 – 1,000 °C
Fuel	[illegible]	[illegible]	[illegible]	[illegible]	[illegible], Short Hydrocarbons (CH_4, etc.)	
Charge Carrier (Water Cavity)	H^+ (O_2[illegible]	[illegible]	[illegible]	[illegible]	[illegible]$_3^{2-}$ (O_2)	O^{2-} (H_2)
Product Water State	Liquid Product		Operation defines product water state		Vapor, externally separated	
Contamination Sensitivity	Very High	High	High	High	Very Low	
Terrestrial Markets C = Commercial, I = Industrial, R = Residential	Transportation, Logistics, Stationary Power (C, I, & R)	Under Development	Stationary Power (C & I)	Stationary Power (C & I)	Stationary Power (C & I)	Stationary Power (C, I, & R)

Currently Under Consideration for Aerospace Applications

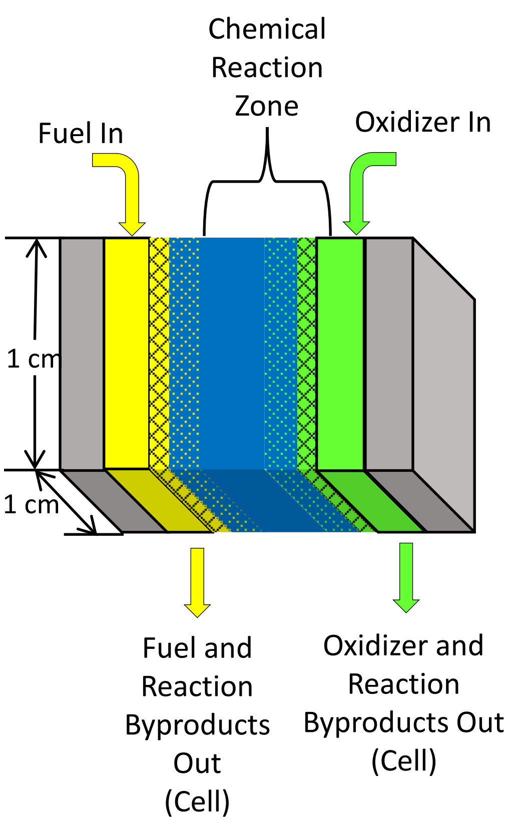
Viable Aerospace Electrochemistry Options

	PEM	Alkaline	Solid Oxide
Key Notes	• Common for mobile terrestrial applications • Terrestrial systems vent Oxygen to remove product water from stack • Mature for terrestrial applications; Needs development for Aerospace	• Very established terrestrial industrial electrolysis technology (chlor-alkali, H_2 production) • Heritage Flight design no longer manufactured in US	• Common for stationary terrestrial applications • Terrestrial systems vent hydrogen to remove product water from stack • Mature for terrestrial applications; Needs development for Aerospace
Advantages	• Rapid reaction kinetics enable transient load response capability • Minimal start times (typ. < 1 min) • Demonstrated high pressure operation (400 psig fuel cell, 12 ksi electrolysis) • Solid polymer electrolyte eliminates migration of acidic electrolyte	• Reaction kinetics enable transient load response capability in many applications • Wide range of acceptable wetted materials • Demonstrated operation for industrial applications • Select designs have demonstrated reversible operation	• Wide range of fuels • Can be configured to internally reform hydrocarbons • High tolerance to contaminants (CO is a fuel) • Resistant to freezing when stored • Select designs have demonstrated reversible operation
Disadvantages	• Very sensitive to CO or Sulfur contaminants • Water-based electrolyte limits temperature regimes • Limited list of acceptable wetted materials (especially at high pressures)	• Very, very sensitive to CO_2 contamination • Electrolyte seeping/weeping a significant issue • Performance sensitive to solution concentration • Typically have very small differential pressures • Water-based electrolyte limits temperature regimes	• Ceramic electrolyte prevents transient load response capability • Ceramic electrolyte limits start-up times to 10's of minutes to hours • Seals need development for Aerospace applications • Limited to low-pressure applications
Development Areas	• Expanded Temperature Range (Currently 4ºC to 85ºC) • Improved life / Reduced Performance Degradation Rates • Improved Contamination Tolerance • Reversibility (Amphiphilic surface treatments) • Cost Reductions • Balance of Plant (supporting components) life, maintainability	• Improved life / Reduced Performance Degradation Rates • Reversible system operation • Elevated Pressures • Balance of Plant (supporting components) life, maintainability	• Expanded Temperature Range (Currently 650ºC to 1050ºC) • Thermal Cycling Capability • Improved life / Reduced Performance Degradation Rates • Seals (currently pressure-limited) • Cost Reductions • Balance of Plant (supporting components) life, maintainability

Basic Construction

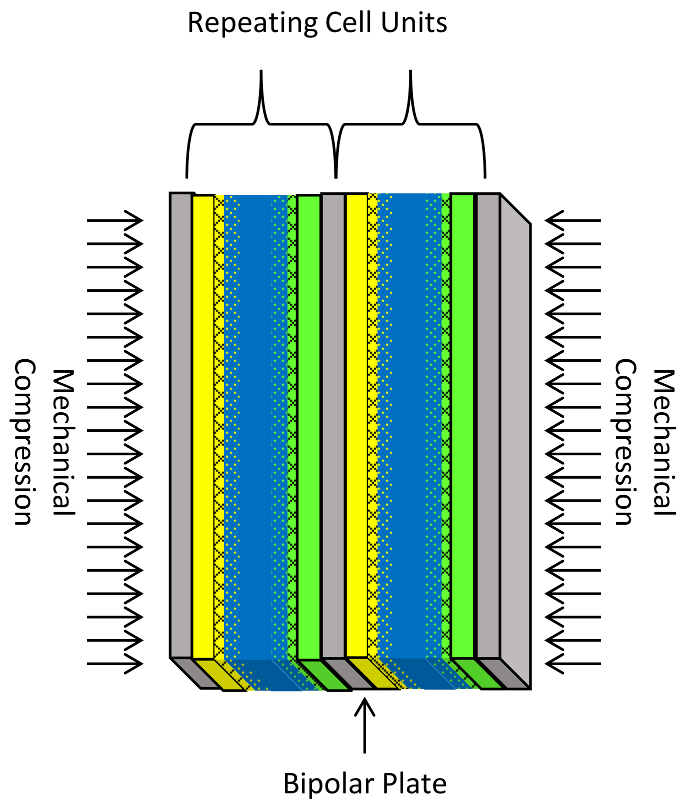
Unit Cell

Fundamental Working Unit



Cell Stack

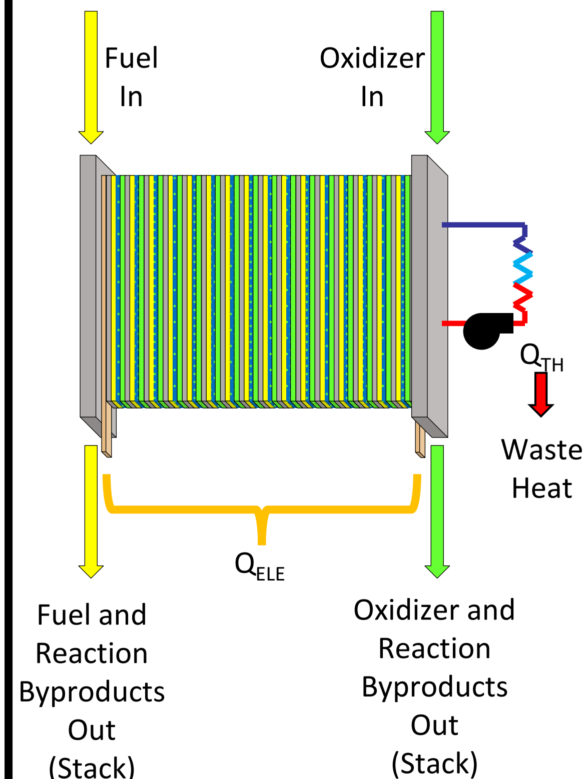
"Filter-Press" Design



Not Shown:
Fluid Manifolds connecting process fluids to each cell

Cell Stack Assembly

Base System Unit



Electrochemical Systems

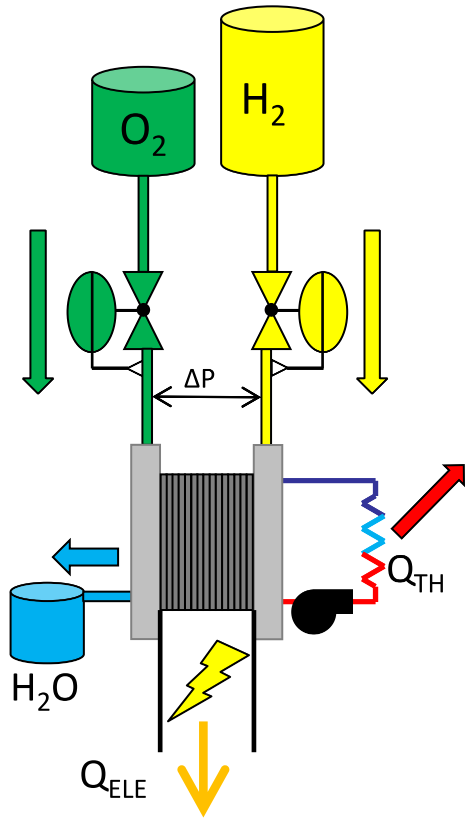
Primary Fuel Cell

Fuel Cell Applications

- Primary power
- RFC Discharge power
- Operational duration based on reactant storage

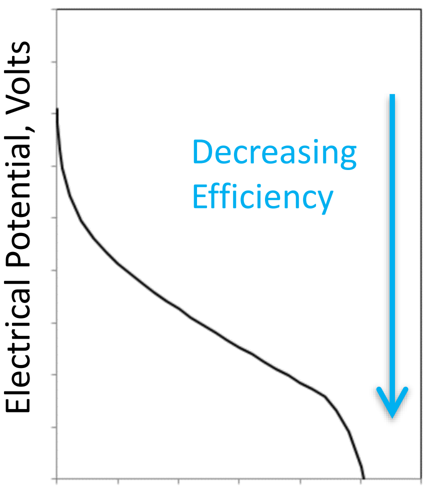
Discharge Power Only

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



Discharging

Fuel Cell Performance



Current Density, mA/cm²

Increasing Current

Increasing Waste Heat

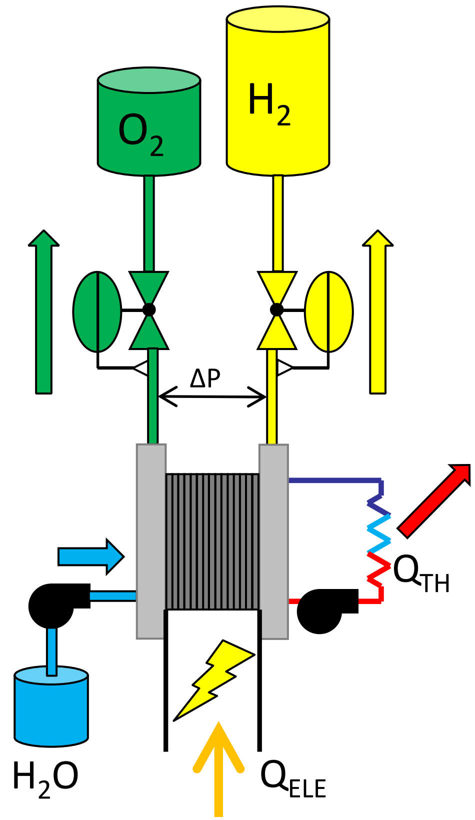
Electrolysis

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

Chemical Conversion

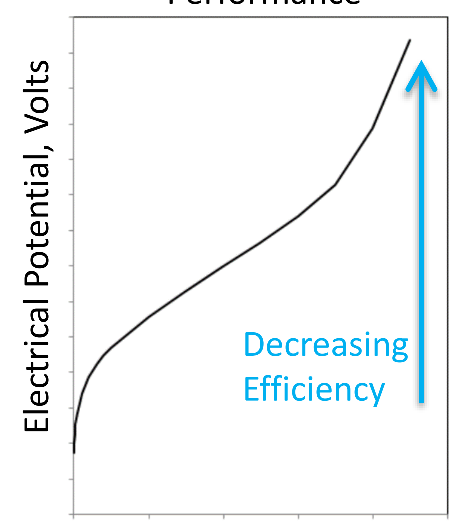
$2H_2O + 4e^- \rightarrow 2H_2 + O_2 + \text{Heat}$



Charging

(Typically, from Solar Arrays)

Electrolysis Cell Performance



Current Density, mA/cm²

Increasing Current

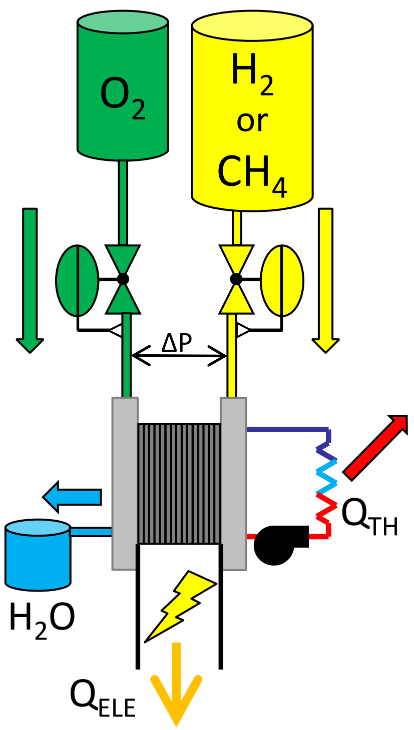
Increasing Waste Heat

Electrochemical Systems

Primary Fuel Cell

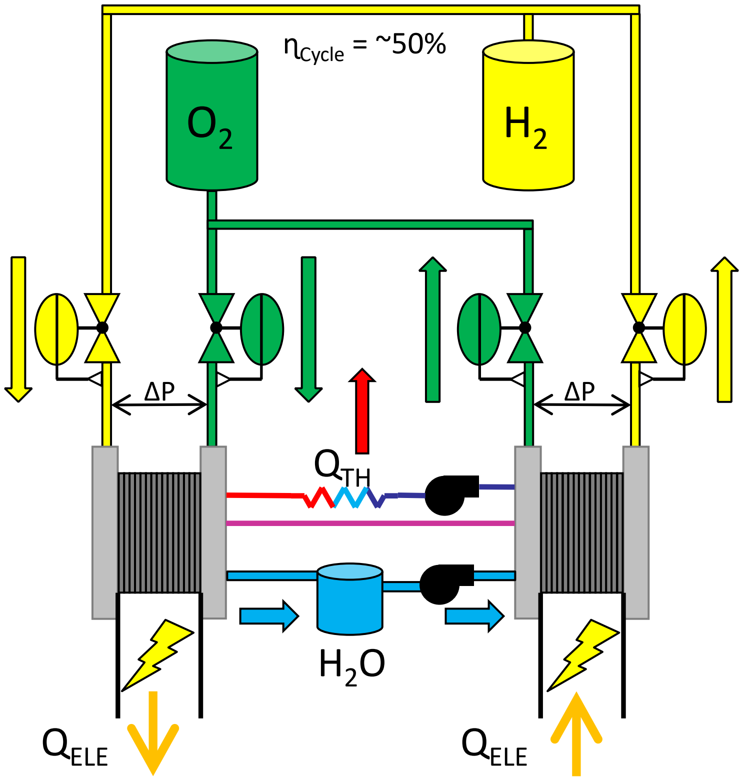
Discharge Power

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



Regenerative Fuel Cell

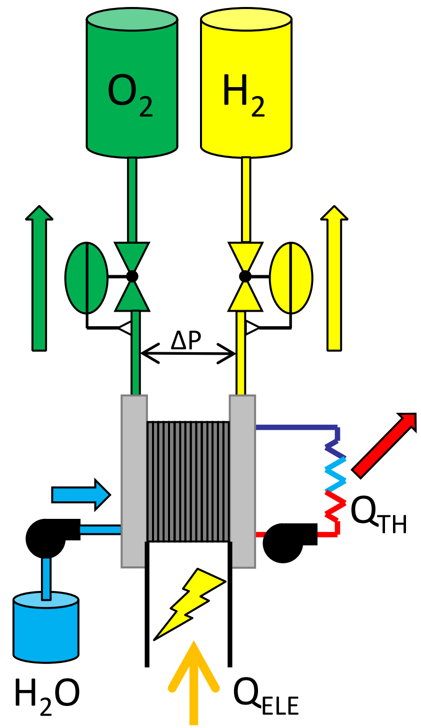
Energy Storage



Electrolysis

Product Generation

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

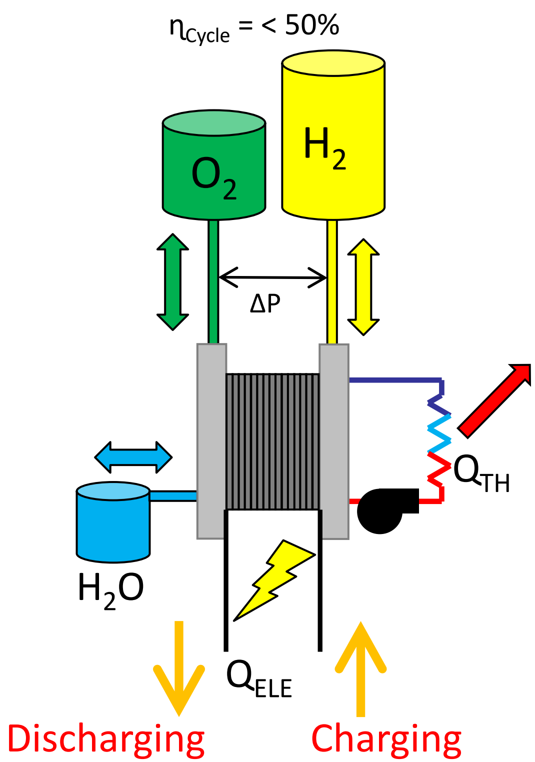


Regenerative Fuel Cell = Fuel Cell + Interconnecting Fluidic System + Electrolysis

Electrochemical Systems

Unitized RFC

Energy Storage System

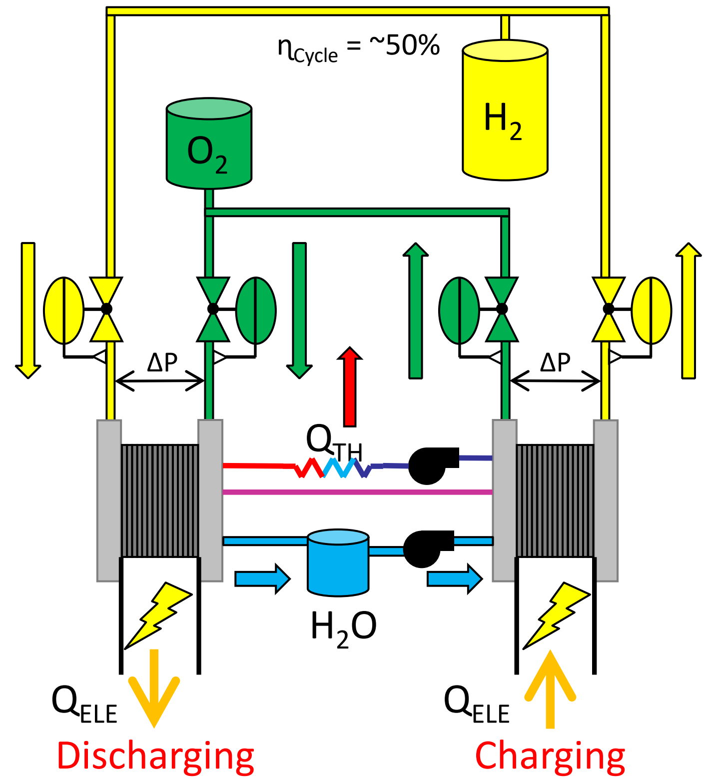


Notes

- Limited by water management (only viable with single-phase fluid systems)
- Operational pressure very limited – tank mass often supersedes reactant mass
- No viable <u>system</u> demonstrated to date

Discrete RFC

Energy Storage System



Notes

- Water management complicated
- Multiple electrolyte chemistries successfully demonstrated proof-of-concept systems
- Commercial H_2/air systems available with η_{cycle} = <10% (telecom back-up power)

Primary RFC System Sizing Parameters

These parameters most influence the Specific Energy of an RFC System

Parameter[1]	Units	Function	Influences
Thermal Environment[2,3]	°C	Specifies thermal and water management requirements	Roundtrip efficiency, specific energy, recharge system requirements, thermal management requirements
Energy Storage Quantity	kW•hr	Specifies reactant mass	Specific energy, thermal management requirements
Discharge Power	kW	Specifies fuel cell stack and fluid system size	Roundtrip efficiency, recharge system requirements, thermal management requirements
Recharge Power Availability[4]	kW profile	Specifies electrolyzer and fluid system size	Roundtrip efficiency, specific energy, recharge system requirements, thermal management requirements
Design Number of Lunar Equator Day/Night Cycles	#	Influences component and system reliability requirements	Mass, Volume

Notes:

(1) Ranked in order of decreasing impact magnitude;

(2) Highly dependent on location and architecture; Selections can increase or decrease RFC specific energy

(3) Least researched/developed element of RFC system designs

(4) Assumes a solar power (PV) system for the entire lander that both recharges the RFC and powers science payloads during lunar day

Fuel Cell Power Generation

Fuel cells provide primary direct current (DC) electrical power

- *Use pure to propellant-grade O_2 / H_2 or O_2 / CH_4 reactants*
- *Uncrewed experiment platforms*
- *Crewed/uncrewed rovers*
- *Electric aircraft / Urban Air Mobility (UAM)*

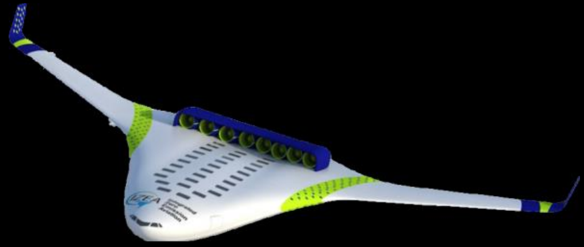
Applications

- *Electric Aircraft / Urban Air Mobility: 120 kW to > 20 MW*
- *Lunar / Mars Landers: ~ 2 kW to ≤ 10 kW*
- *Lunar / Mars surface systems: ~ 2 kW to ≤ 10 kW modules*
- *Venus atmosphere sensor platforms: ≤ 1 kW*

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)
Design Study for Hydrogen Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage

Blue Origin Lunar Lander Baselined Fuel Cell Power as primary power source

Concept H_2-fueled Aircraft for the Integrated Zero Emission Aviation (IZEA)
ULI activity led by Florida State University



H_2 and O_2 Reactant Generation

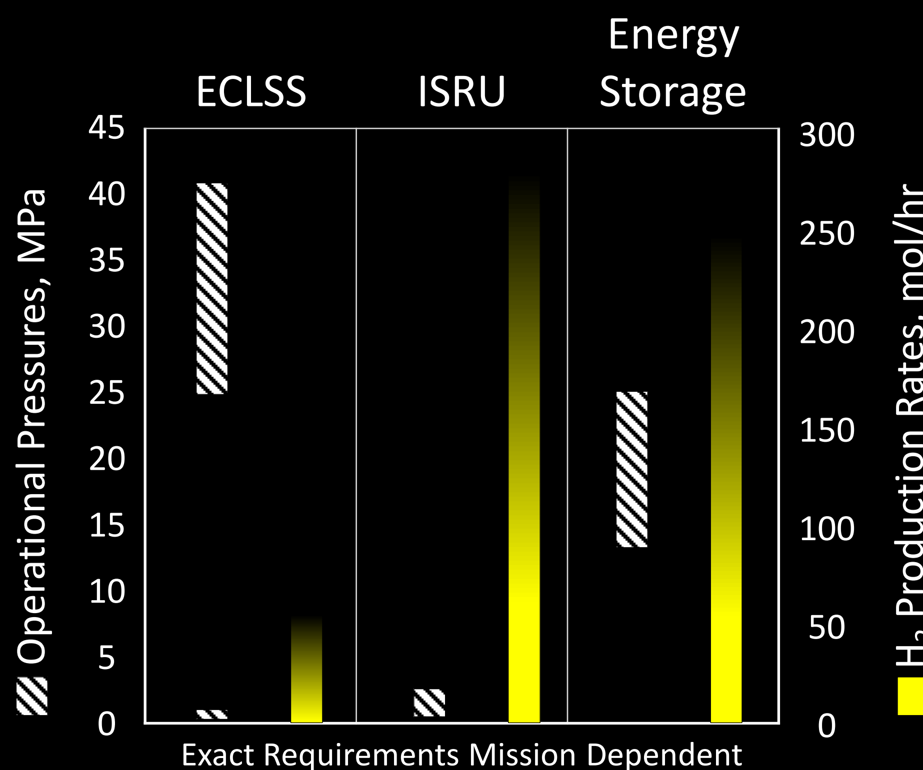
Electrolysis

- *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*
- *In-situ Resource Utilization (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*

Processing Mined Lunar Water-Ice

- *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



All applications Power and Mass Constrained

Energy Storage

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-hour maintenance interval*

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

Known Technical Gaps

SPACE

1. **Availability:**
   - New technologies not yet flight qualified for microgravity applications
   - No flight-qualified fuel cell since the end of the Space Shuttle Program
   - Domestic Industrial supply chain compromised
2. **Operational Life:**
   - Pure oxygen reactants provide challenging operational environment
   - Pure water introduces long-term failure mechanisms
   - Space Missions have limited maintenance options
   - Long dormancy periods with large thermal variations
3. **System Integration:**
   - Advantageously leveraging different systems to reduce overall vehicle mass
   - Putting it all together in a low-mass cost-effective package
   - Demonstrating component and system reliability
4. **Specific Energy:**
   - Increase system-level specific energy to increase vehicle payload capacity

AERONAUTICS

1. **Thermal Management**:
   - High Power applications = large thermal loads
   - Fundamental electrochemical technologies limited by thermal management
   - Electric aircraft have multiple distributed thermal loads
   - Advanced Hydrogen combustion technologies have localized thermal loads
2. **Manufacturing Scale:**
   - Domestic supply chain capabilities limit component size / scale
3. **Power Management and Distribution:**
   - High Electrical Current
   - High Power / High Voltage Conversion
   - Wiring mass
4. **On-board Hydrogen Management:**
   - Cryogenic Storage
   - Hydrogen Monitoring
   - Hydrogen Materials
5. **System Integration:**
   - Putting it all together in a cost-effective package for commercial applications

B334 Fuel Cell Test Laboratory

B334 is designed for safe & versatility:

- Layered safety systems to protect personnel, facility & test articles
- Class I Division II Group B rated facility
- Test cell dimensions: 24’ X 18’ (432 ft^2, 7308 ft^3)
- Poured concrete walls with reinforced re-bar
- Cell rating: ≤ 125 kW (H_2/air or H_2/O_2)
- Remote facility controls/monitoring
- Unattended operations (24/7)
- Test cells equipped with camera systems
- Each test cell independent ventilation exhaust systems

Facility Capabilities:

- Existing Test Capabilities
  - Primary Fuel Cells
  - Regenerative Fuel Cells
  - High Pressure Water Electrolysis Systems
  - Electrochemical Compression Systems
- Existing fluid services:
  - General-use (shop) air
  - Research air
  - Nitrogen
  - Hydrogen
  - Oxygen
  - Vacuum source
  - Chilled Water
- Existing Electrical services:
  - PLC Data Acquisition and Control System
  - Programmable Load Bank
  - Programmable Power Supply

Selected Projects

Fuel Cell and Hydrogen Activities

- **Applications**
  - Lunar Lander Power
  - Lunar Night Survivability
  - In situ Resource Utilization
  - Environmental Control and Life Support
- **Technology Focus Areas**
  - Primary Fuel Cells: sub-components, system components, system integration
  - Regenerative Fuel Cell Energy Storage: sub-components, system components
  - Water Electrolysis: sub-components, system components, system integration
- **Funding Organizations**
  - Exploration Systems Development Mission Directorate (ESDMD)
    - Human Lander Systems (HLS)
    - Extravehicular Activity and Human Surface Mobility Program (EHP)
  - Space Technologies Mission Directorate
  - Aeronautics Research Mission Directorate
- **External**
  - Department of Energy (DOE) Hydrogen Interagency Taskforce (HIT)
  - Naval Underwater Warfare Center (NUWC)
  - Ohio Fuel Cell and Hydrogen Coalition (OFCC)

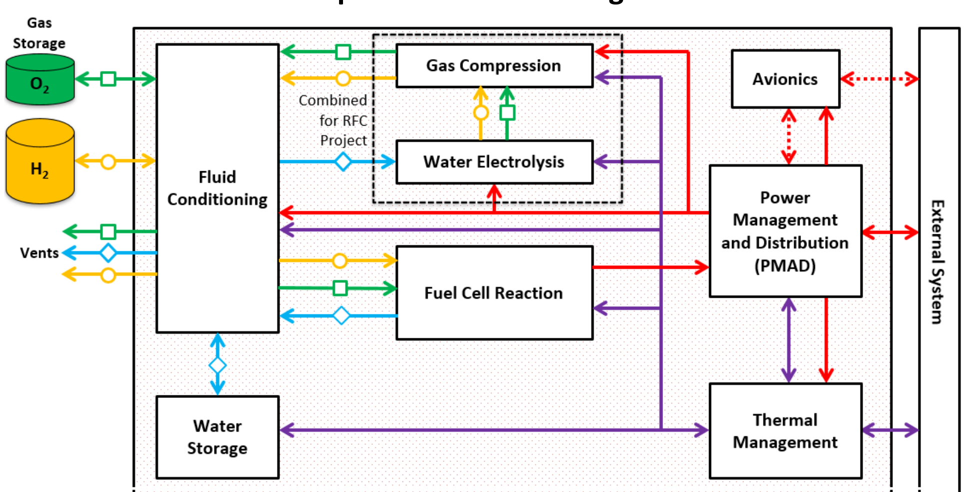
Regenerative Fuel Cell Project

- Available energy storage technologies have low specific energies (W·hr/kg) imposing unacceptable mass onto lunar surface missions
- NASA funds research of multiple technologies to maximize specific energy, including hydrogen (H_2) / oxygen (O_2) regenerative fuel cell (RFC) energy storage technology
- RFC project to assess viability of optimized discrete system technology for potential inclusion into lunar surface missions

Regenerative Fuel Cell Project Overview

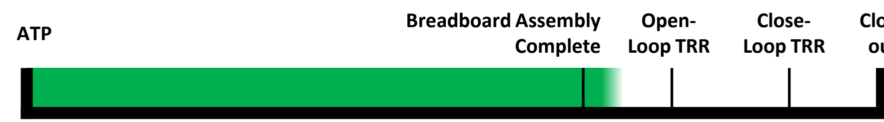
Design & Build H_2 / O_2 RFC System	• 50 psia Fuel Cell stack (Infinity Fuel Cell and Hydrogen) • 1800 to 2500 psia Electrolyzer (Giner) • Self-supporting sub-systems • Automated control system
≥ 2 month autonomous closed-loop test under laboratory conditions	• Full system pressures and multiple cycles • Open-loop operation for system functional verification • Closed-loop operation for reactant purity verification

Simplified RFC Block Diagram



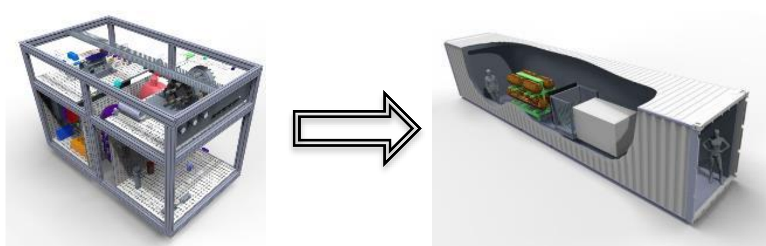
System Legend

	H_2		H_2O		Power
	O_2		Thermal		Data/Com



GRC
- Component Verification Testing
- Breadboard System Assembly
- Breadboard System Verification
- Breadboard Open-loop Testing

ATF
- RFC Breadboard System Closed-loop Testing



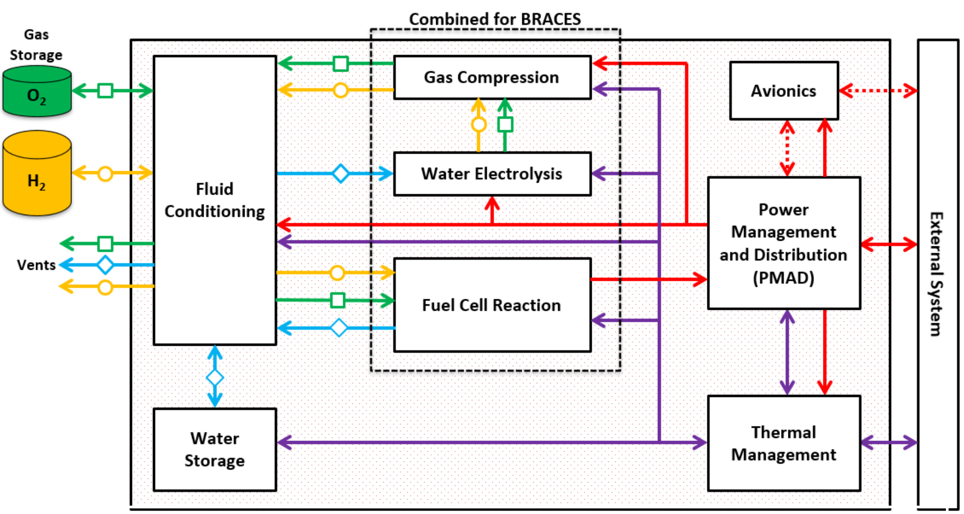
Bi-furcated Reversible Alkaline Cell for Energy Storage (BRACES) Tipping Point

- Available energy storage technologies have low specific energies (W·hr/kg) imposing unacceptable mass onto lunar surface missions
- NASA funds research of multiple technologies to maximize specific energy, including hydrogen (H_2) / oxygen (O_2) regenerative fuel cell (RFC) energy storage technology
- BRACES project to assess viability of *unitized stack* design for potential inclusion into lunar surface missions

BRACES Tipping Point Overview

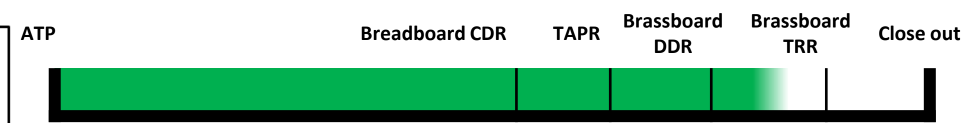
Design & Build Unitized Stack (pH Matter)	• 250 bar (~3600 psia) Unitized stack • Unitized stack to demonstrate electrolysis and fuel cell reactions
Design & Build Test Systems (pH Matter)	• Automated independent control system • Breadboard system for Laboratory testing • Brassboard system for Thermal-Vacuum test
Brassboard Verification Testing (GRC)	• Verify open-loop operation for system cyclic operation and performance metrics

Simplified BRACES Diagram



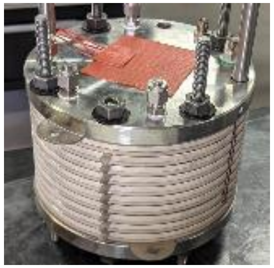
System Legend

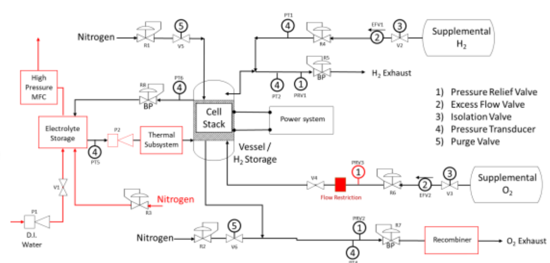
	H_2		H_2O		Power
	O_2		Thermal		Data/Com



pH Matter
- Component Development (Stack)
- Breadboard System Design, Assembly, and Verification

GRC
- Breadboard System Open-loop Laboratory Testing (No Reactant Storage)

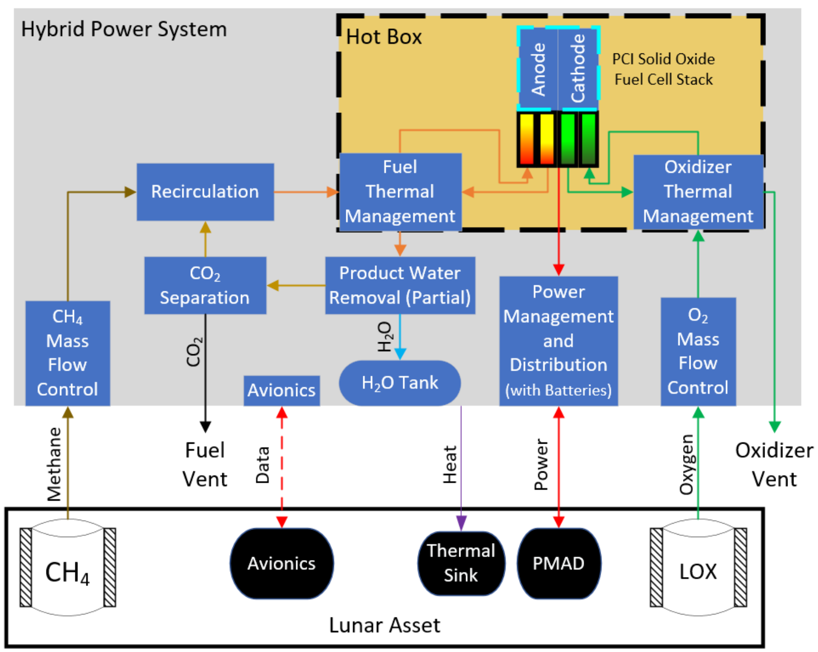




Propellant Fueled Solid Oxide Fuel Cell (PropFC) Tipping Point

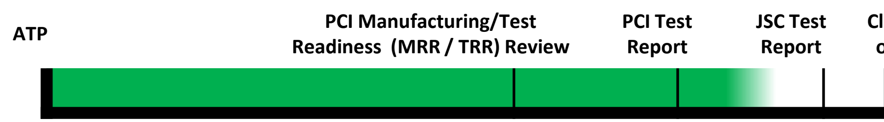
- Advance primary solid oxide fuel cell technology to generate electrical power directly from residual CH_4/LOX propellants
- Advance H_2/air & CH_4/air stack seal design for pure oxygen
- Conduct system-level trade study to evaluate technology for potential inclusion into lunar surface missions

Simplified PropFC Functional Block Diagram



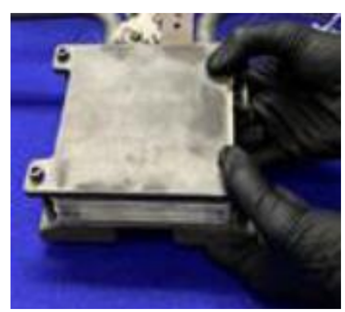
PropFC Tipping Point Overview

Design & Build Fuel Cell Stack (PCI)	• 250-Watt Solid Oxide Fuel Cell stack • H_2/O_2 and CH_4/O_2 reactants
System-level Trade Study (GRC)	• Develop system-level design study • Identify system-level technology gaps
Verification Testing (PCI)	• Envelope and performance testing
Environmental Testing (JSC)	• Shock and Vibration testing



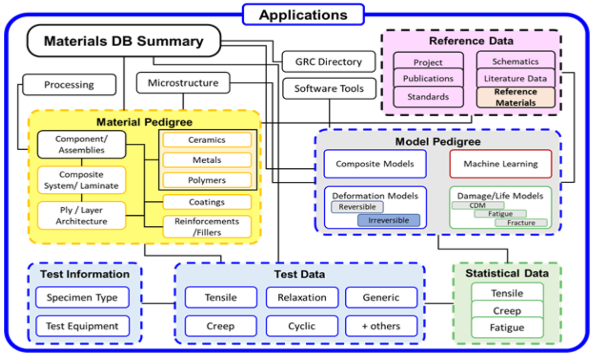
PCI
- Component Development
- Component Verification Testing

JSC
- Stack Performance Testing
- Stack Environmental Testing

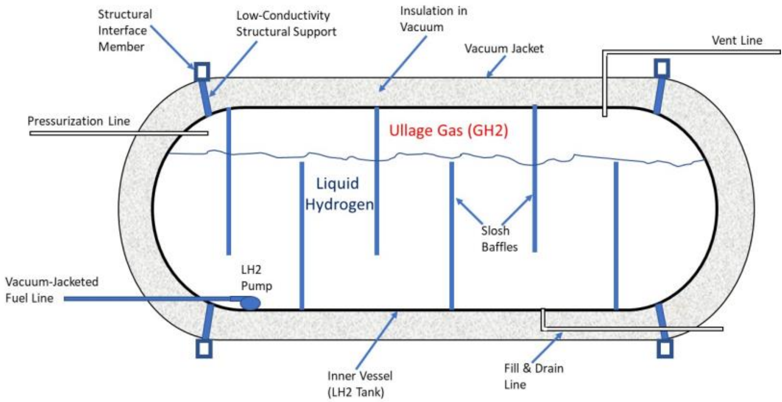


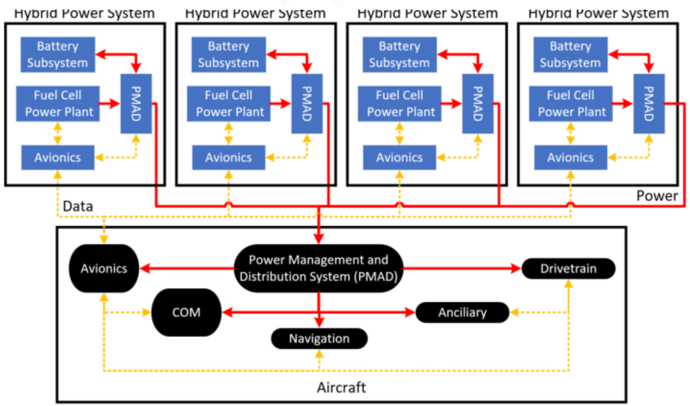
Commercially-viable Hydrogen Aircraft for Reduction of Greenhouse Emissions (CH2ARGE)

- **Study activity to inform NASA's role in emerging Hydrogen Aircraft movement and support development of Zero Carbon / H_2 Aircraft.**
  - Identify options for NASA to contribute to evolving H_2 aviation movement
  - Identify differentiation points between NASA and other players
  - Identify stakeholders / contributors for NASA engagement
- **Technology Development areas:**
  - Aircraft Architectures / Packaging
  - Aircraft Structures
  - Cryogenic Hydrogen Management
  - Primary Fuel Cell Power Plants
  - Power Management and Distribution
  - Thermal Management
- **Project Methodology**
  - Survey existing literature, government development programs, industry activities
  - Identify notional technical requirements
  - Identify gaps between existing capabilities and notional requirements
  - Develop notional Roadmaps to close identified technical gaps
  - Use Machine Learning (ML) tools for new materials / R&D options
  - Coordinate activities with other agencies (DOE HIT, AFRL, ARL, etc.)
  - Coordinate activities with external partners (academia, industry, etc.)
- **Participating Centers: GRC (Lead), LaRC, ARC**



NASA GRC ICME Schema





THANK YOU FOR YOUR ATTENTION

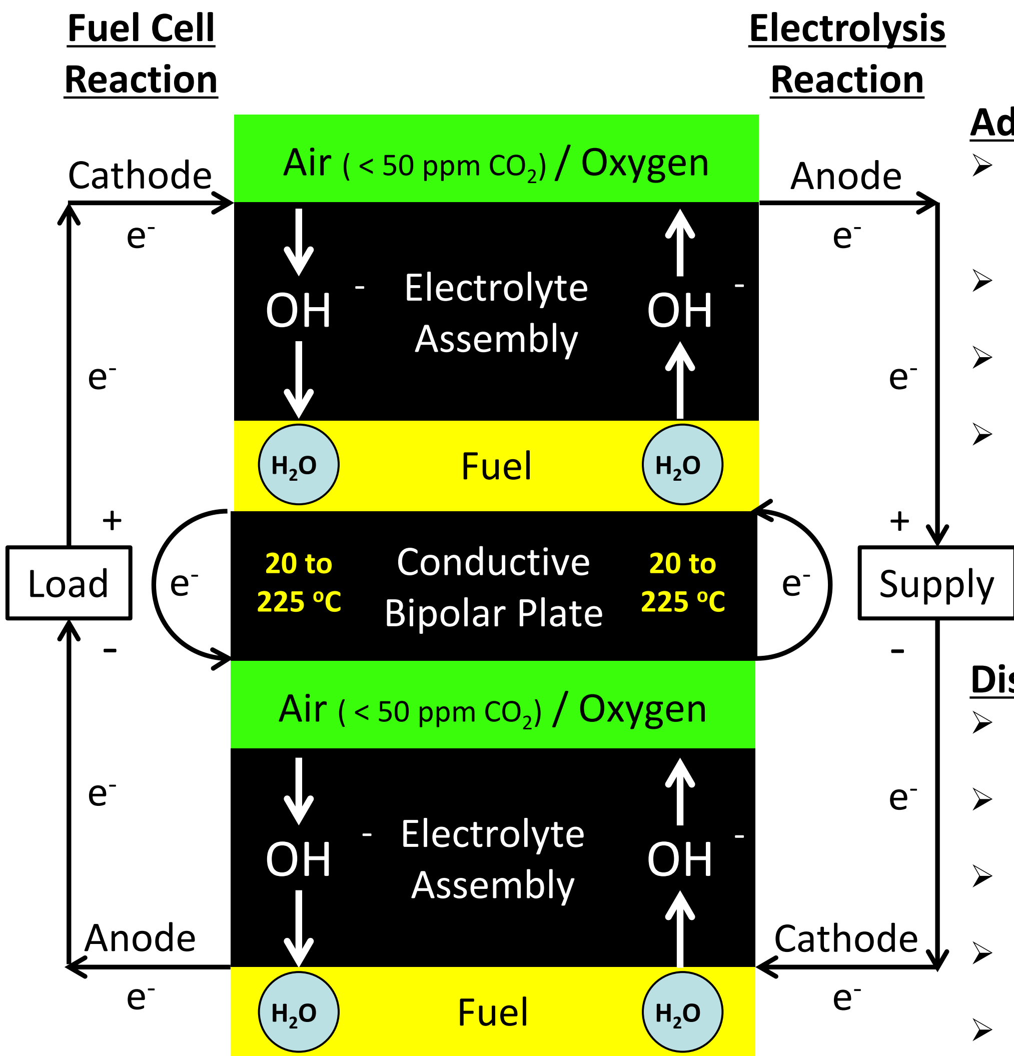
Questions/Comments -

Back-up

Alkaline Reactions

Key Notes:
- Very established terrestrial industrial electrolysis technology (e.g. chlor-alkali, H_2 production)
- Heritage Flight design no longer manufactured in US

Development Areas:
- Improved life / Reduced Performance Degradation Rates
- Reversible system operation
- Elevated Pressures
- Balance of Plant (supporting components) life, maintainability



Advantages:
- Reaction kinetics enable transient load response capability in many applications
- Wide range of acceptable wetted materials
- Demonstrated operation for industrial applications
- Select designs have demonstrated reversible operation

Disadvantages:
- Very, very sensitive to CO2 contamination
- Electrolyte seeping/weeping a significant issue
- Performance sensitive to solution concentration
- Typically have very small differential pressures
- Water-based electrolyte limits temperature regimes

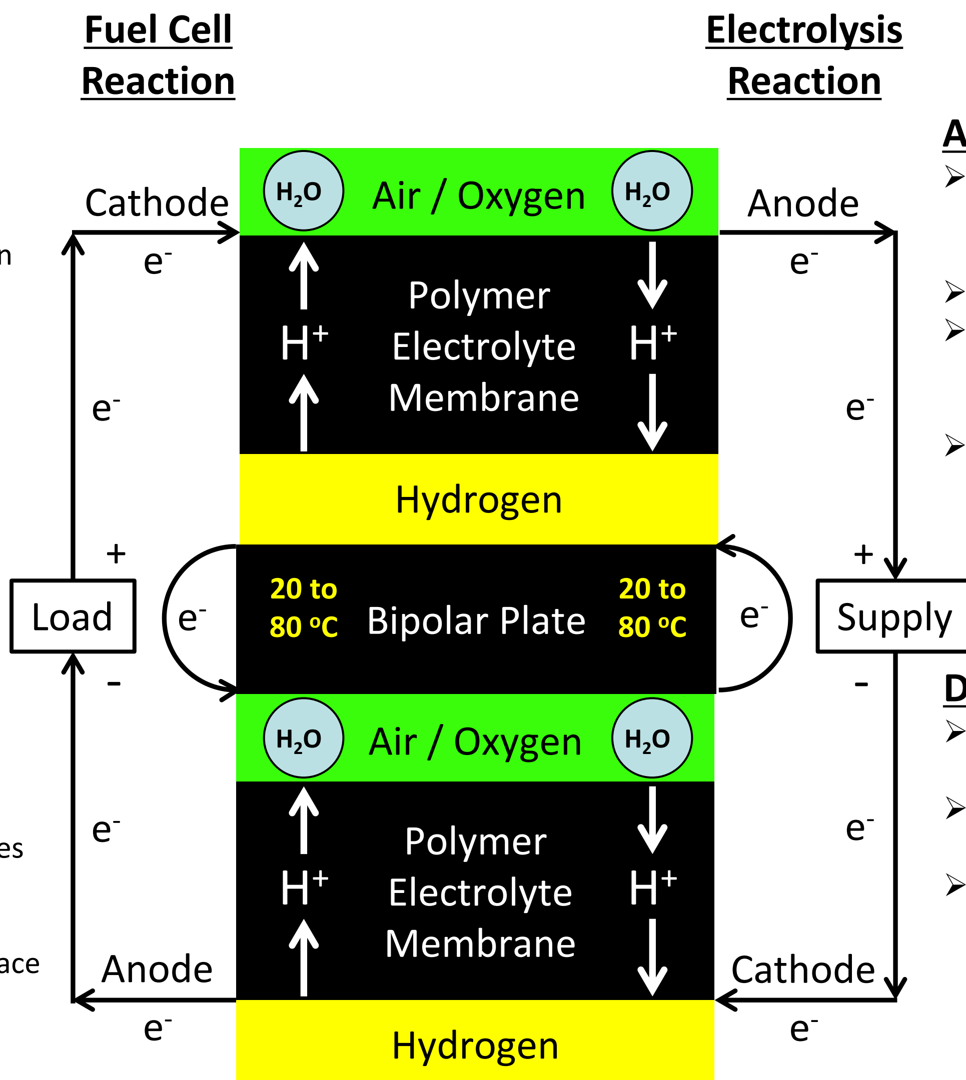
Proton Exchange Membrane (PEM) Reactions

Key Notes:

- Common for mobile terrestrial applications
- Terrestrial systems vent Oxygen to remove product water from stack
- Mature for terrestrial applications;
  Needs development for Aerospace

Development Areas:

- Expanded Temperature Range (Currently 4ºC to 85ºC)
- Improved life / Reduced Performance Degradation Rates
- Improved Contamination Tolerance
- Reversibility (Amphiphilic surface treatments)
- Cost Reductions
- Balance of Plant (supporting components) life, maintainability



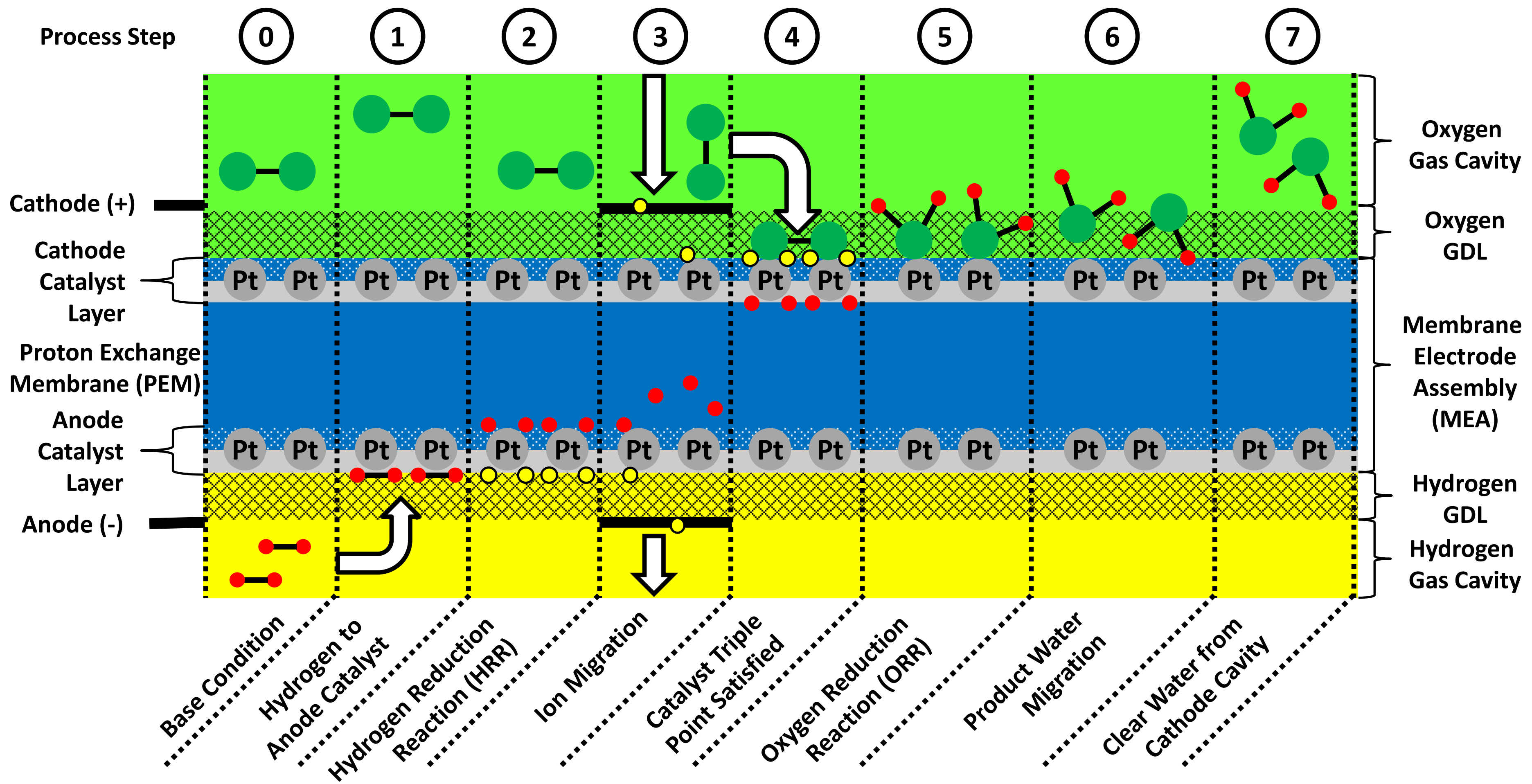
Advantages:

- Rapid reaction kinetics enable transient load response capability
- Minimal start times (typ.< 1 min)
- Demonstrated high pressure operation (400 psig fuel cell, 12 ksi electrolysis)
- Solid polymer electrolyte eliminates migration of acidic electrolyte

Disadvantages:

- Very sensitive to CO or Sulfur contaminants
- Water-based electrolyte limits temperature regimes
- Limited list of acceptable wetted materials (especially at high pressures)

PEM Fuel Cell Reaction

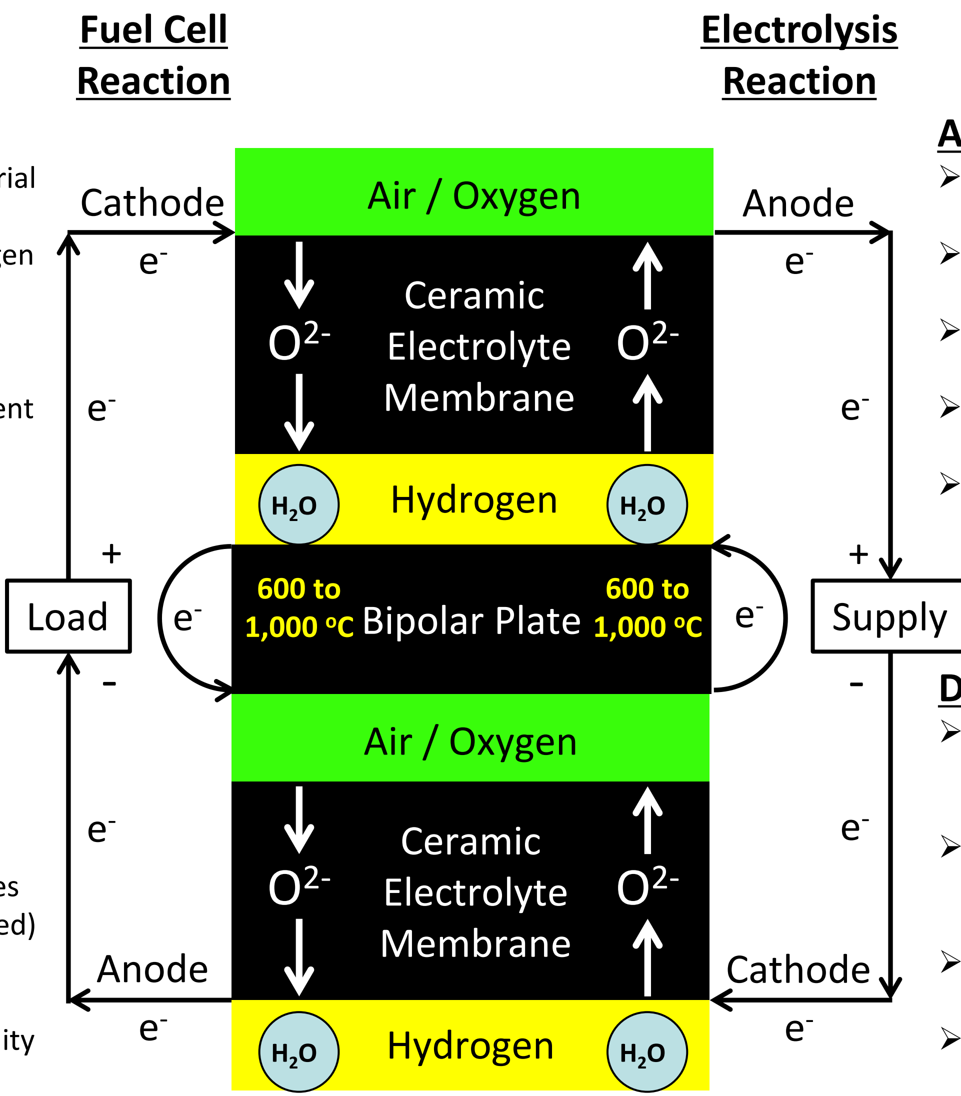


Chemical Bond = —
Electron (e^-) = ○
Hydrogen (H^+) = ●
Oxygen (O^{2-}) = ●
Gas Diffusion Layer = GDL

$$\text{Net Reaction: } 2_gH_2 + {}_gO_2 \xrightarrow{Heat+4e^-} 2_lH_2O$$

Solid Oxide Reactions

Key Notes:
- Common for stationary terrestrial applications
- Terrestrial systems vent hydrogen to remove product water from stack
- Mature for terrestrial applications; Needs development for Aerospace

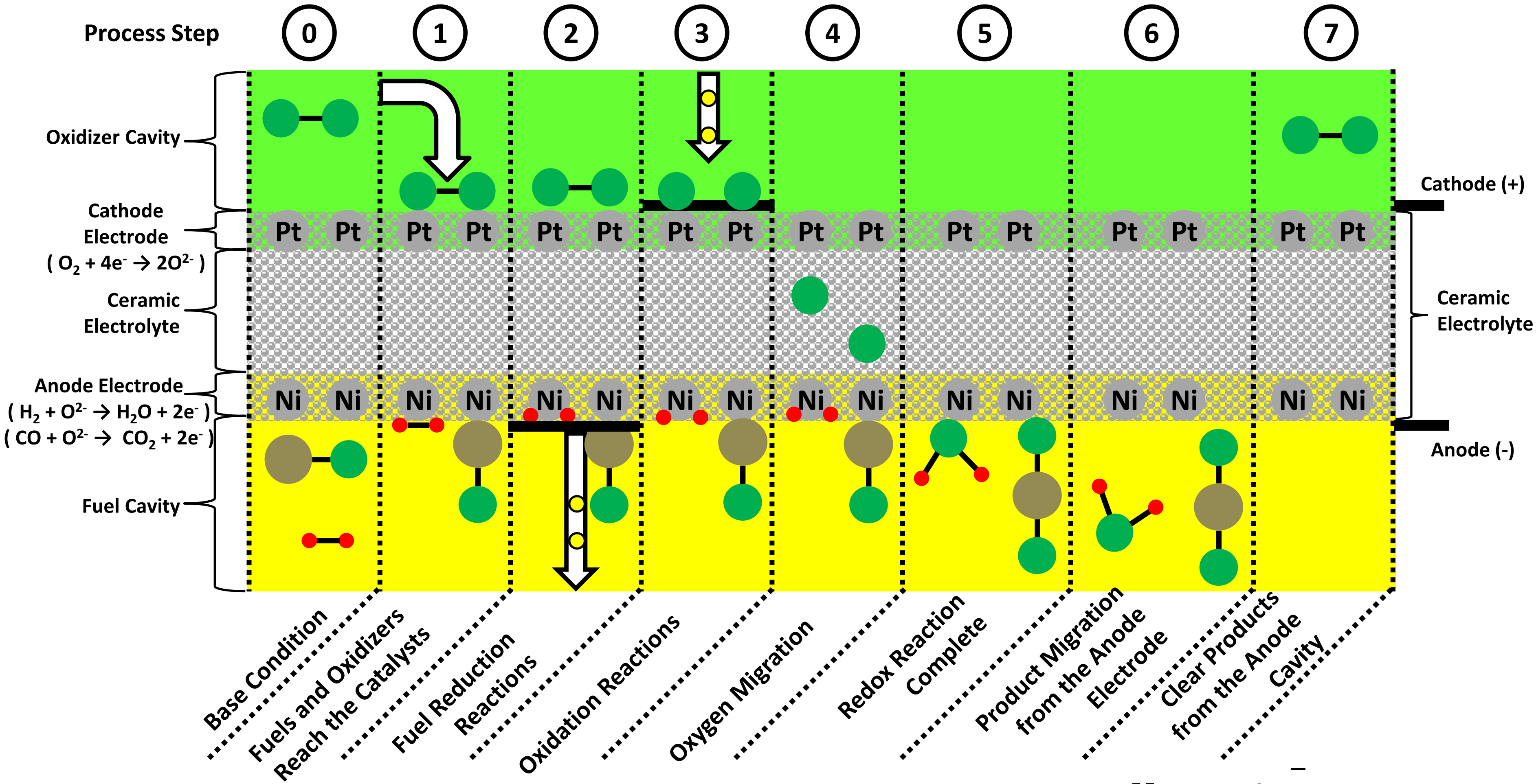


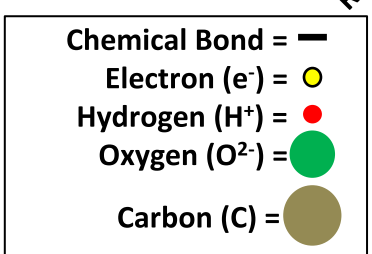
Development Areas:
- Expanded Temperature Range (Currently 650°C to 1050°C)
- Thermal Cycling Capability
- Improved life / Reduced Performance Degradation Rates
- Seals (currently pressure-limited)
- Cost Reductions
- Balance of Plant (supporting components) life, maintainability

Advantages:
- Wide range of fuels (H_2, CH_4, CO, etc.)
- Can be configured to internally reform hydrocarbons
- High tolerance to contaminants (CO is a fuel)
- Resistant to freezing when stored
- Select designs have demonstrated reversible operation

Disadvantages:
- Ceramic electrolyte prevents transient load response capability
- Ceramic electrolyte limits start-up times to 10's of minutes to hours
- Seals need development for Aerospace applications
- Limited to low-pressure applications

Solid Oxide Fuel Cell Reaction





Net Reactions:

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

$$2CO + O_2 \xrightarrow{Heat+4e^-} 2CO_2$$

Electrochemical Systems

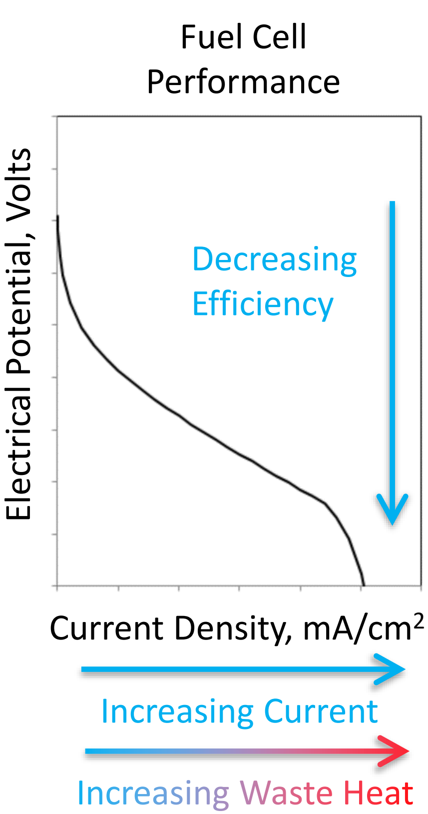
Primary Fuel Cell

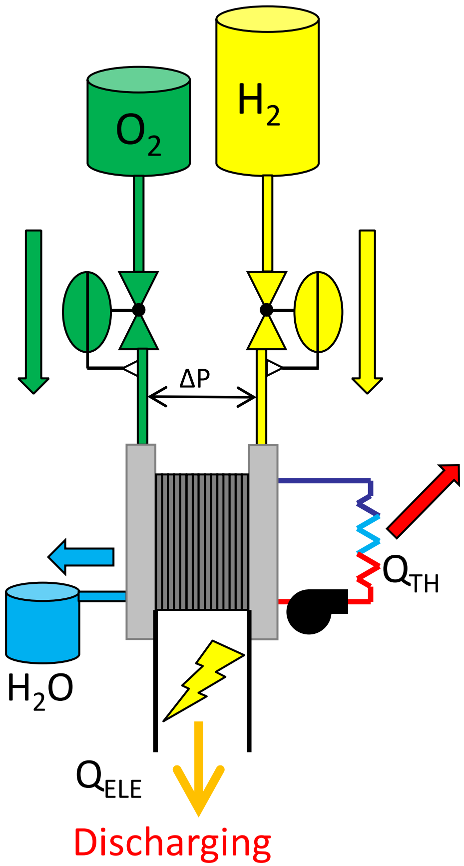
Fuel Cell Applications

- Primary power
- RFC Discharge power
- Operational duration based on reactant storage

Discharge Power Only

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





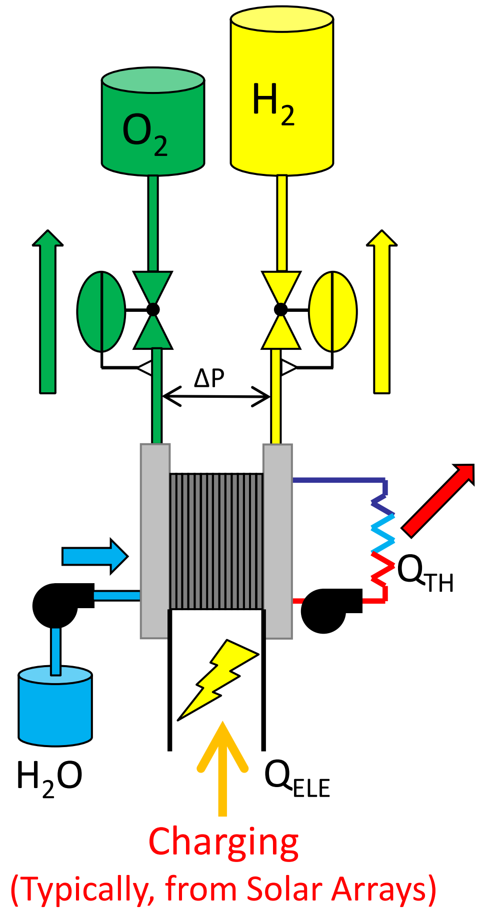
Electrolysis

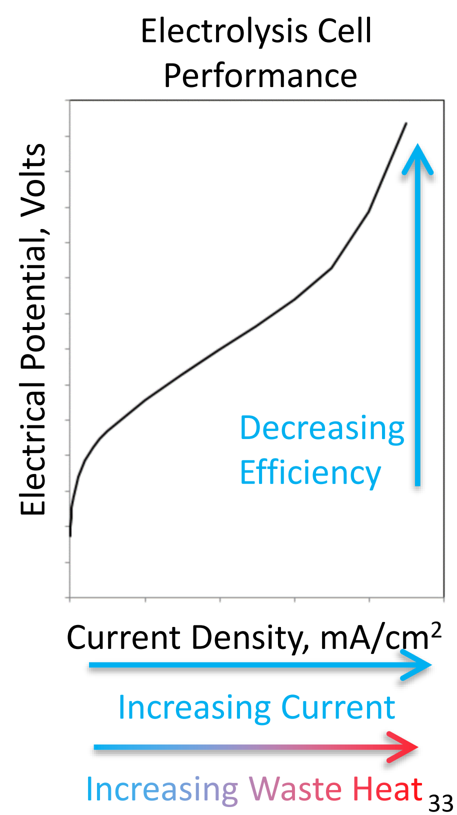
Chemical Conversion

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

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



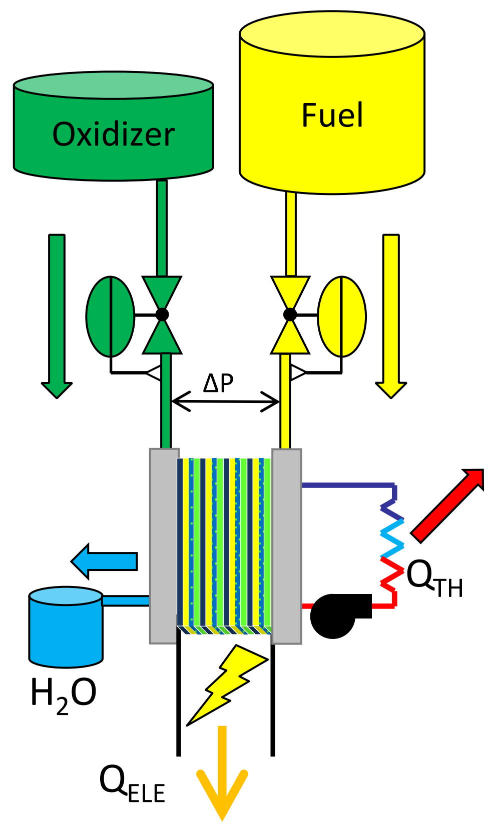


Electrochemical System: Fuel Cell

Discharge Power Only

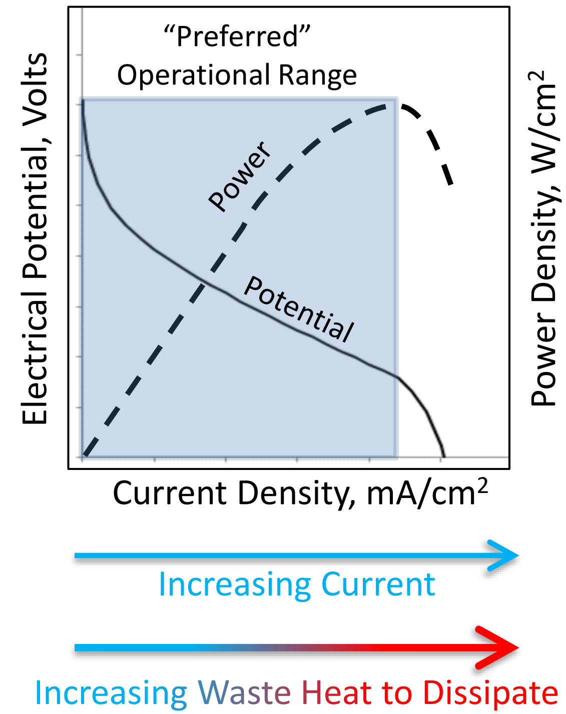
- Primary electrical ***current*** source (voltage indicates conversion efficiency)
- Fluidic analogy
  - Fuel cell ~ fluid "pump"
  - Current ~ electrical "mass flow rate"
  - Voltage ~ electrical "pressure"
- Pure water byproduct for H_2-based fuel cells
  (molecularly pure at catalyst site)
- Water state (gas / vapor) dependent on Fuel Cell Chemistry
- State of reactant storage not relevant to fuel cell stack operation
  (chemical vs compressed vs cryogenic)

Fuel + Oxidizer →
DC Current + Water + Heat



Electrical Load

Fuel Cell Performance

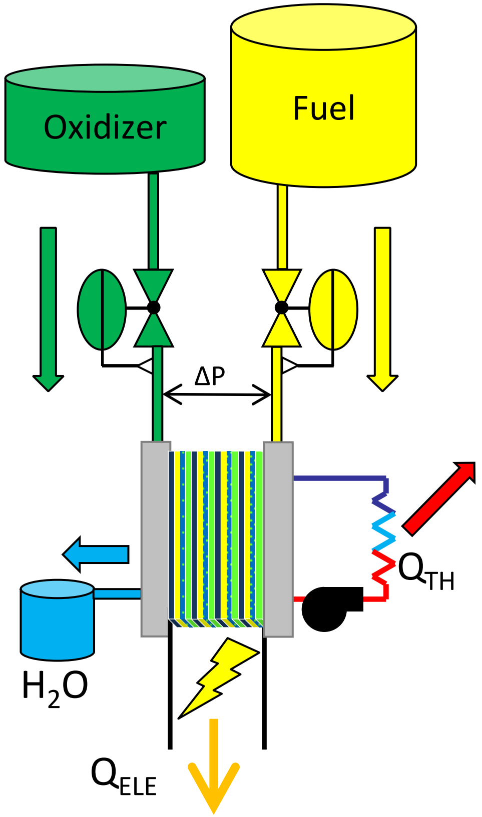


Electrochemical System: Electrolysis

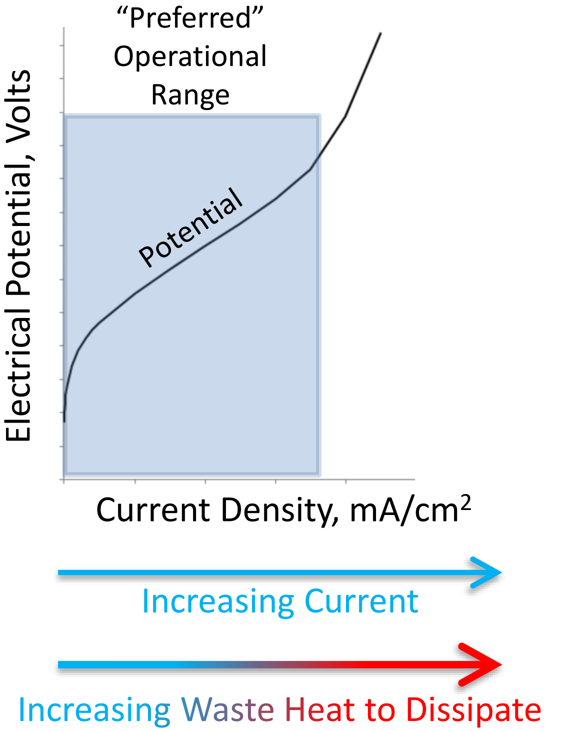
Requires Input Power

- Hydrogen production process for over 100 years
- Green technology if power source is renewable
- Fluidic analogy
  - Current ~ H_2 production rate
  - Voltage ~ H_2 production efficiency
- Source water purity very dependent
  - Electrolysis Chemistry
  - Production efficiency requirements
- State of reactant storage (cryogenic vs compressed) not relevant to electrolysis stack operation
  - Infrastructure Balance of Plant between stack and storage impacted, but stack is not

Fuel + Oxidizer → DC Current + Water + Heat



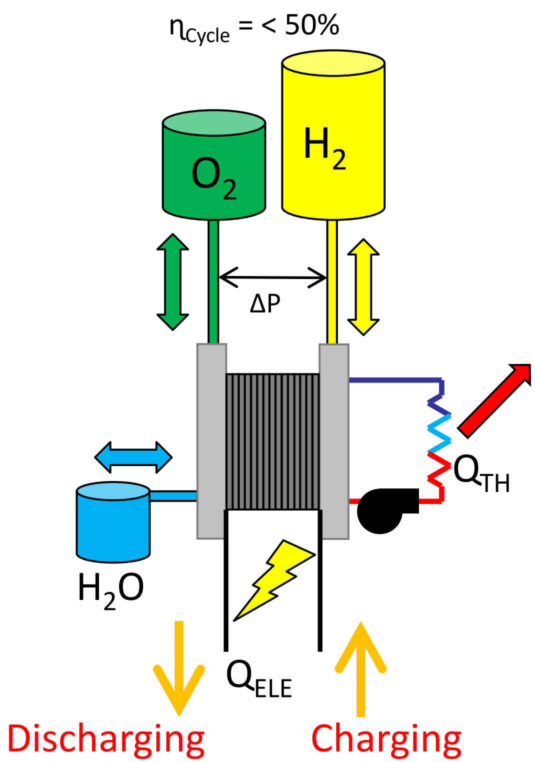
Electrolysis Performance



Electrochemical Systems

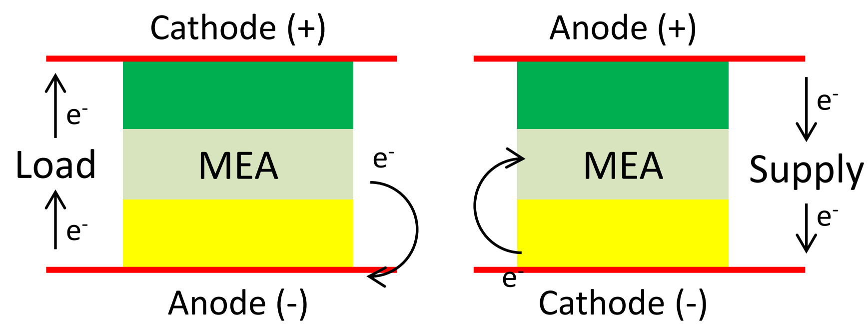
Unitized RFC

Energy Storage System



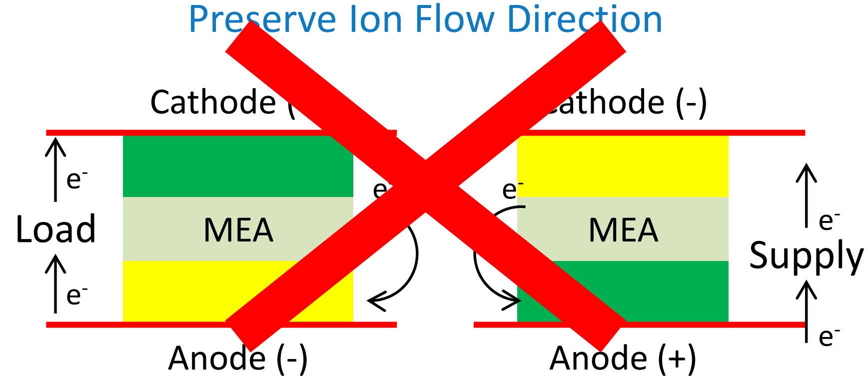
Constant Gas

Change Ion Flow Direction



Constant Electrode

Preserve Ion Flow Direction



Currently not viable for crewed missions