National Aeronautics and Space Administration

Alternative Power Sources for Aerospace Vehicles

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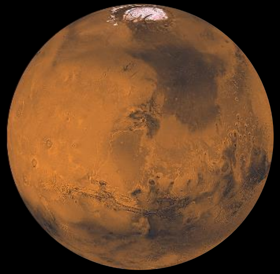
Presentation Overview

- Provide a background of fuel cell power technologies for Aerospace applications:
    - Environments
        - Earth
        - Cis-Earth
        - Lunar
        - Mars
        - Venus
    - Power Generation
        - Primary Fuel Cells (Power)
        - Regenerative Fuel Cells (Energy Storage)
    - Energy Storage
        - Regenerative Fuel Cells (Energy Storage)

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)
Design Study for H_2 Fuel Cell Powered Electric Aircraft using Cryogenic Hydrogen Storage.

Advanced Modular Power Systems (AMPS) Scarab Rover Demonstration
Field demonstration of a H_2 / O_2 Fuel Cell System powering the Carnegie-Mellon Scarab Rover from Compressed Gas Storage.

NASA Fuel Cell Application Environments

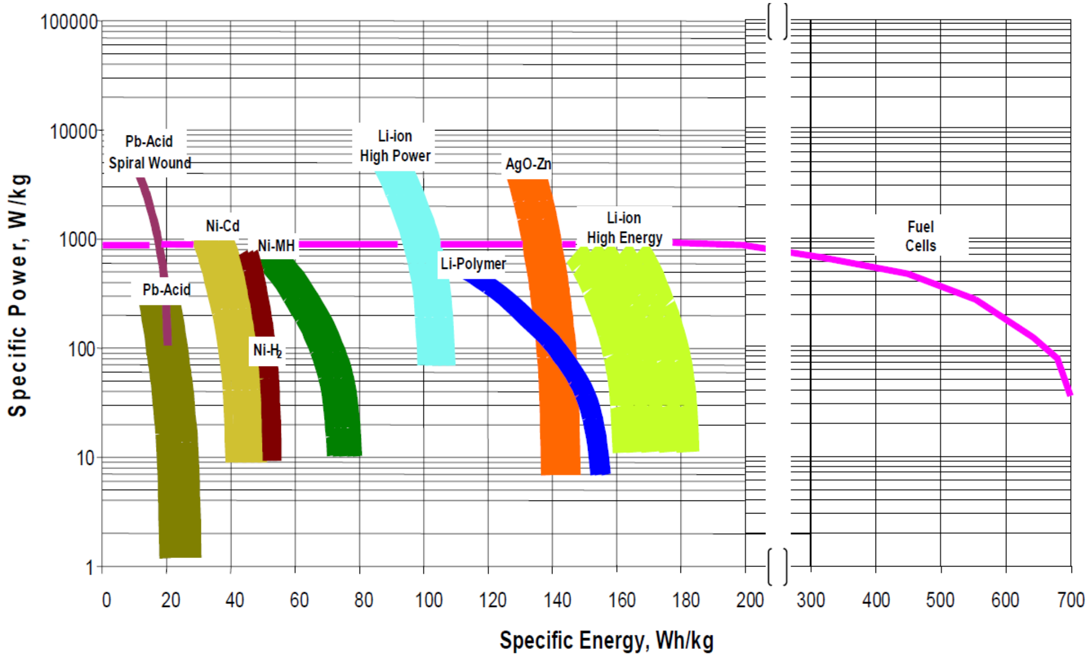


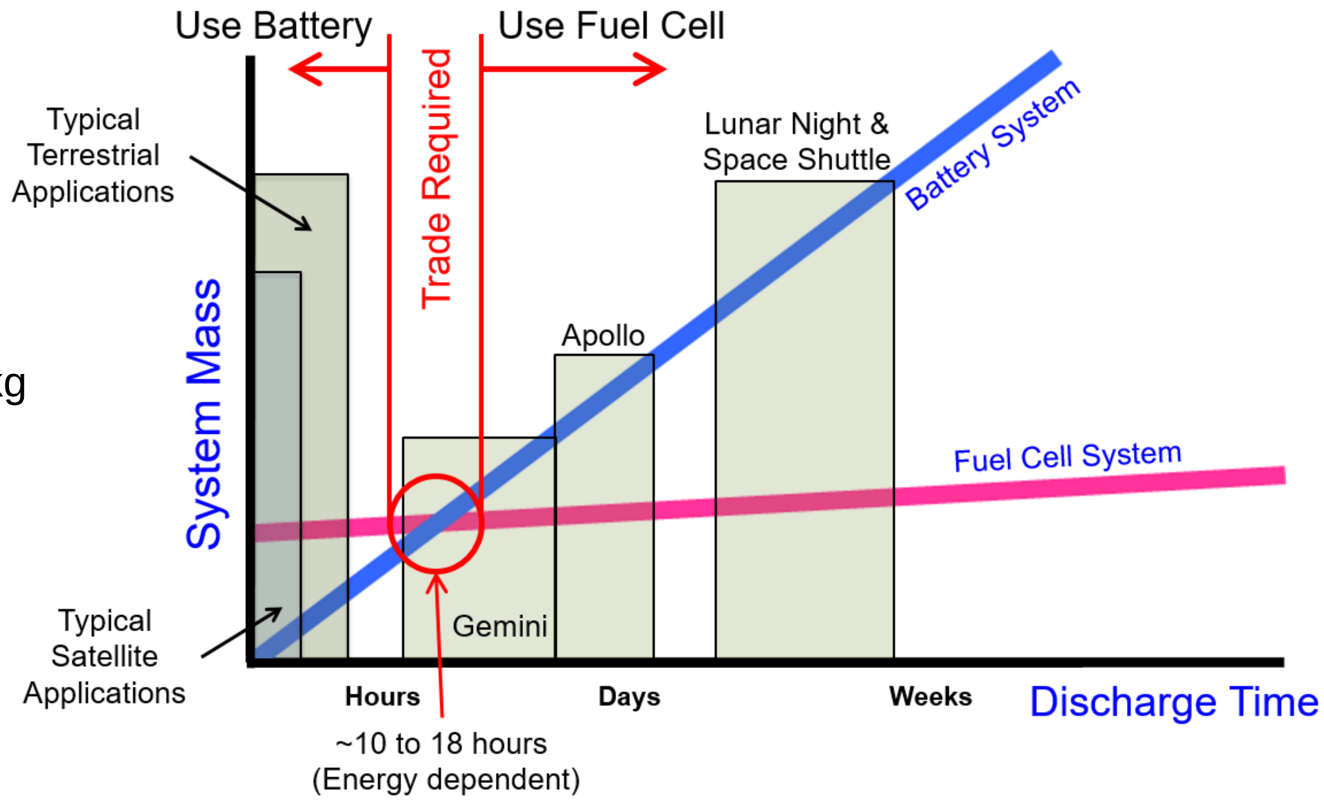
	Earth	**Cis-Earth**	**Mars**	**Moon**	**Venus**
Pressure	1 Atm	Not Applicable	0.006 Atm	Not Applicable	91.8 Atm
Temperature	-89 °C to +57 °C	**Deep Space: -270 °C	-89 °C to +57 °C	-173 °C to +105 °C	~ 464 °C
Gravity	1.0	None (μg)	0.4	1.6	0.9
Atmosphere	N_2, O_2, H_2O	None	CO_2, Ar, N_2	None	CO_2, N_2
Considered Fuel Cell Application Locations	Launch Vehicles Electric Aircraft Electric Vehicles Electric Submersibles	Crewed Spacecraft with High Flight Dynamics (no PV arrays)	Landing Craft Rovers Habitats	Landing Craft Rovers Habitats	Atmospheric Sensor Platforms

See SLS-SPEC-159 – Cross-Program Design Specification for Natural Environments (DSNE) – Rev D

Space Power and Energy Options

- Technologies are <u>*Complementary*</u> not <u>*Competitive*</u>
  - No power or energy storage technology meets all requirements for all applications
  - Each technology has a place within the overall exploration space
  - Energy Storage Metric = Specific Energy (W·hr/kg)
    - Packaged Li-ion Battery Systems ~ 160 W·hr/kg
    - Regenerative Fuel Cell Systems <100 to >600 W·hr/kg based on location and energy requirements





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

Fuel Cell Systems in Space

Aerospace

Space Shuttle Fuel Cell

(1979 - 2012)

<u>Differentiating Characteristics</u>

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

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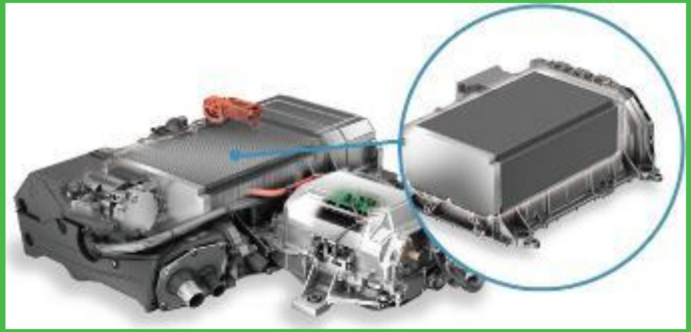
Terrestrial



Toyota Mirai Fuel Cell[1]

<u>Differentiating Characteristics</u>

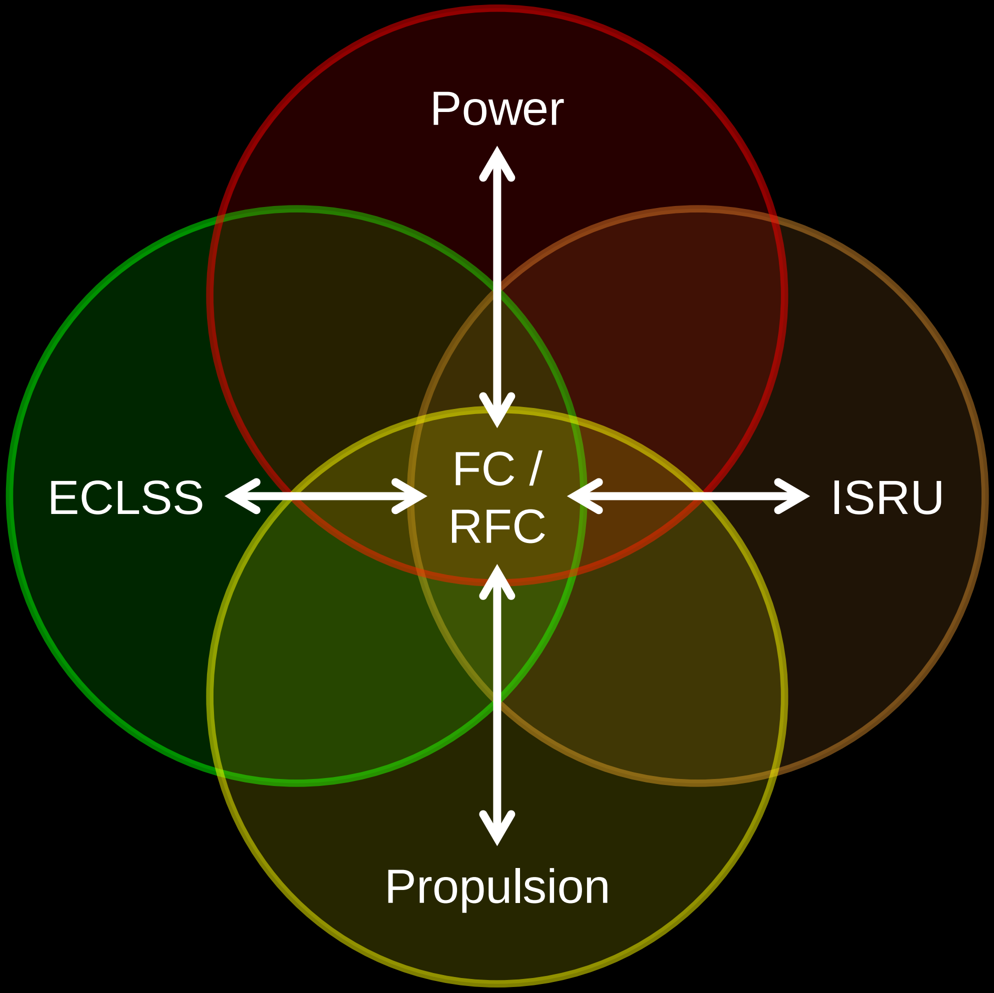
- Atmospheric Air (conditioned, excess flow)
- High air flow drives water removal

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

Electrochemical Interoperability

The core fuel cell and water electrolysis chemical reactions share common reactants and power/energy requirements across support multiple aerospace electrochemical applications.



Legend
ECLSS = Environmental Control and Life Support Systems
FC = Fuel Cell (Primary Power)
ISRU = In Situ Resource Utilization (On-site Production)
PMAD = Power Management and Distribution
RFC = Regenerative Fuel Cell (Energy Storage)

Electrochemical System Chemistry Options

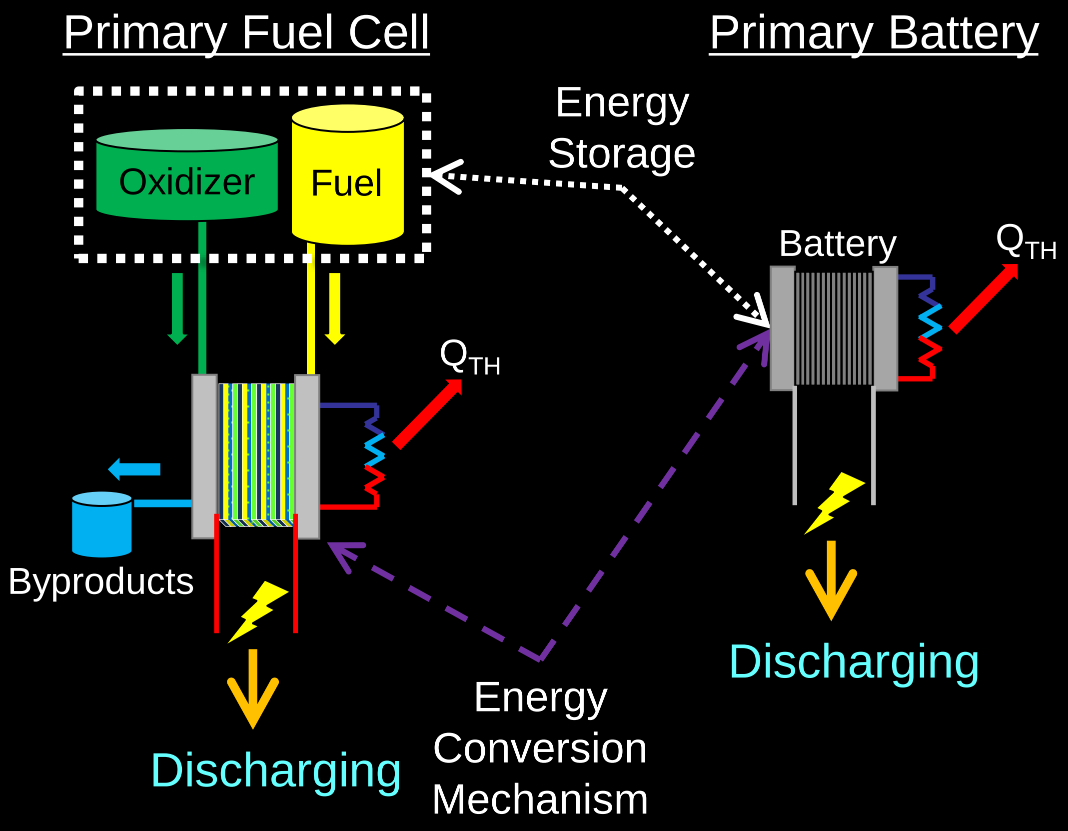
	Low Temperature		Moderate Temperature		High Temperature	
Cell Type	Proton Exchange Membrane (PEM)	Alkaline Polymer Membrane (AEM)	Alkaline	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Electrolyte (State)	Ionic Polymer Membrane (Solid)	Anionic Polymer Membrane (Solid)	Alkaline Solution in 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 / Hydrophilic Surfaces)	Very Limited (Hydrophobic / Hydrophilic Surfaces)	Configuration Limited	Configuration Limited	High (Pressure-limited)	High (Pressure-limited)
Operating Temperature	10 – 80 ˚ C				-650 ˚ C	600 – 1,000 ˚C
Fuel	Pure H_2				CO, Short Hydrocarbons (CH_4, etc.)	
Charge Carrier (Water Cavity)	H^+ (O_2)				CO_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

All information dated March 2022

Primary Fuel Cells vs. Primary Battery

Electrical Power to enable and augment exploration activities



Primary Metric = Specific Power (W / kg)

Batteries store energy <u>intimately</u> with the energy conversion mechanism

Primary fuel cells store energy <u>remotely</u> from the energy conversion mechanism

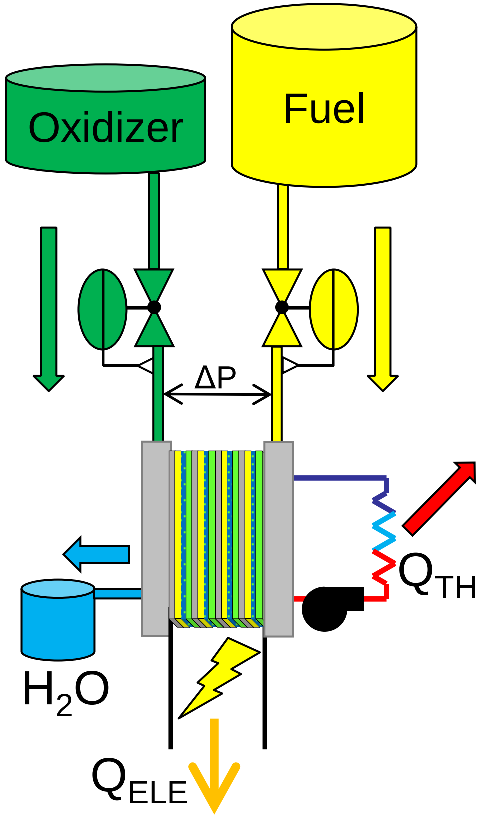
- Different Hazards and Mitigations
  - Batteries sensitive to Thermal Runaway
  - Fuel Cells sensitive to Material Compatibility and Process Fluid management issues
- Different Voltage to State-of-Charge (SoC) relationships
  - Battery voltage dependent on quantity of stored energy
  - Fuel Cell voltage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

Basic Electrochemical Systems: Fuel Cell

- 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 (cryogenic vs compressed) not relevant to fuel cell stack operation

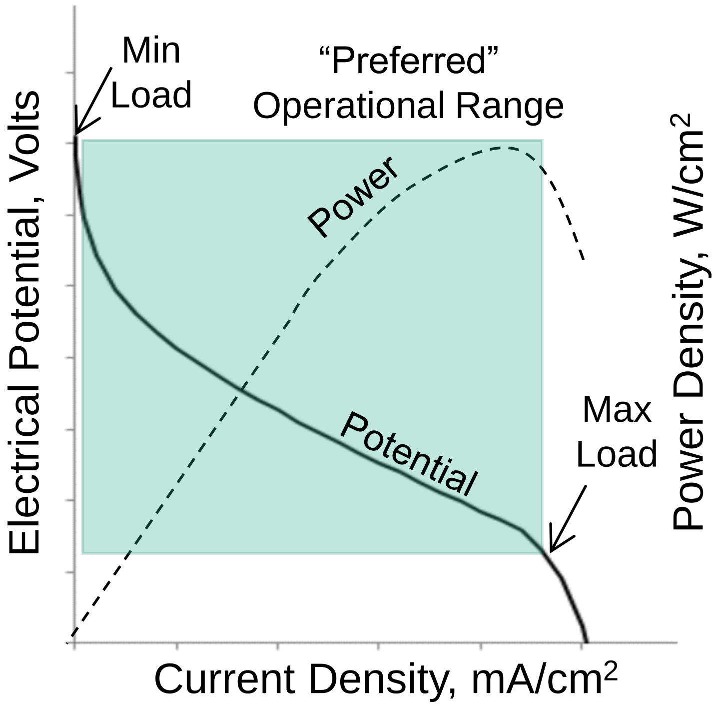
Discharge Power Only

Fuel + Oxidizer → DC Current + Water + Heat



Electrical Load

Fuel Cell Performance



Increasing Current

Increasing Waste Heat to Dissipate

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)*

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

Applications

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

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

NASA's all-electric X-57 Maxwell prepares for ground vibration testing at NASA's Armstrong Flight Research Center in California.
Credits: NASA Photo / Lauren Hughes

Known Aeronautic Technical Gaps

1. Thermal management:
   - High Power applications = large thermal loads
   - Electric aircraft have multiple distributed thermal loads
   - Advanced Hydrogen combustion technologies have localized thermal loads
2. Power Management and Distribution
   - High Electrical Current
   - High Power / High Voltage Conversion
   - Wiring mass
3. On-board Hydrogen management
   - Cryogenic Storage
   - Hydrogen Monitoring
   - Hydrogen Materials
4. System Integration
   - Putting it all together in a cost-effective package for commercial applications

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA)

Center for High-Efficiency Electrical Technologies for Aircraft (CHEETA) program to develop, mature, and design disruptive technologies for electric commercial aviation.

- Provide a direct line-of-sight path to
  - Meet/exceed aviation goals for alternative propulsion and energy options
  - An aircraft system with a quiet, efficient propulsion system that produces zero CO_2, NO_X, and particulate emissions
- Research associated technologies
  - Distributed aero-propulsion system integration
  - High-efficiency electrochemical power conversion
  - Flight-weight electric machines and power electronics,
  - Materials and systems for superconducting high-efficiency power transmission
  - Methods for complex system integration and optimization.
  - Unconventional energy storage and power generation architectures (e.g. liquid hydrogen fuel and fuel cell systems)
- Identify Technology Gaps for future research

Principal Investigator: Phillip Ansell
Lead Organization: University of Illinois
Supporting Organizations:

- Boeing
- Chicago State University
- General Electric (GE)
- Massachusetts Institute of Technology (MIT)
- Ohio State University
- Rensselaer Polytechnic Institute
- University of Arkansas
- University of Dayton

Funded by:
Aeronautics Research Mission Directorate (ARMD) Transformative Aeronautics Concepts Program (TACP) University Leadership Initiative (ULI, https://uli.arc.nasa.gov/)

Known Space Technical Gaps

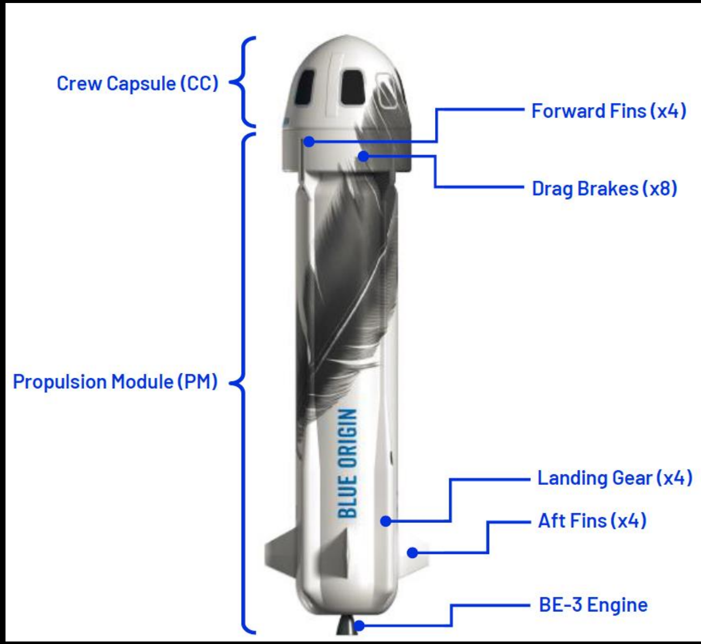
1. Availability:
   - New technologies not yet flight qualified for microgravity applications
   - No flight-qualified fuel cell since the end of the Space Shuttle Program
2. Operational Life:
   - Pure oxygen reactants provide challenging operational environment
   - Space Missions have limited maintenance 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
4. Power Density
   - Increased system-level power density for increased vehicle payload capacity

Space Fuel Cell Power Development Activities

PEM (Nafion-based)

TRL 5^+

1. Space Technology Development
   - Lunar Lander Fuel Cell (LLFC) – Blue Origin
2. Sub-orbital Flight Technology Demonstration
   - Advanced Modular Power and Energy System (AMPES) – Infinity Fuel Cell & Hydrogen
   - Hydrogen Electrical Power System (HEPS) – Teledyne

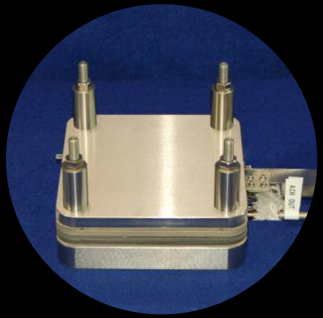


Integrated
New Shepard Vehicle
Crew Capsule and
Propulsion Module

Solid Oxide

TRL 3 to 4

1. Solid Oxide Fuel Cells (SOFC)
   - Surface Power Generation from Lunar Resources and Mission Consumables - Precision Combustion
   - Efficient, High Power Density Hydrocarbon-Fueled Solid Oxide Stack System- Precision Combustion
   - 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



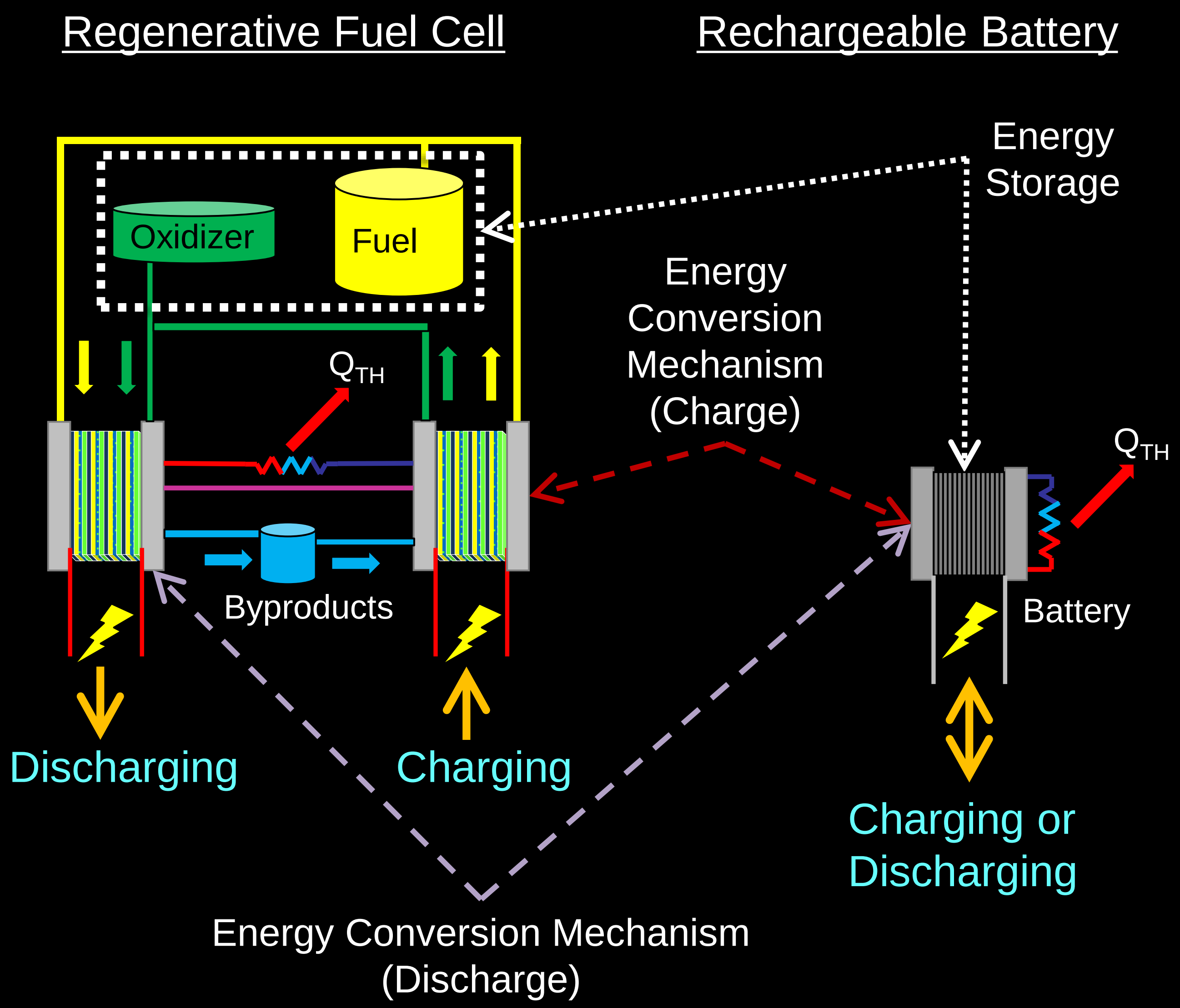
SOFC Sub-Stack for space applications

Funding Sources

NASA Funds	Tipping Point / ACO	SBIR / STTR

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

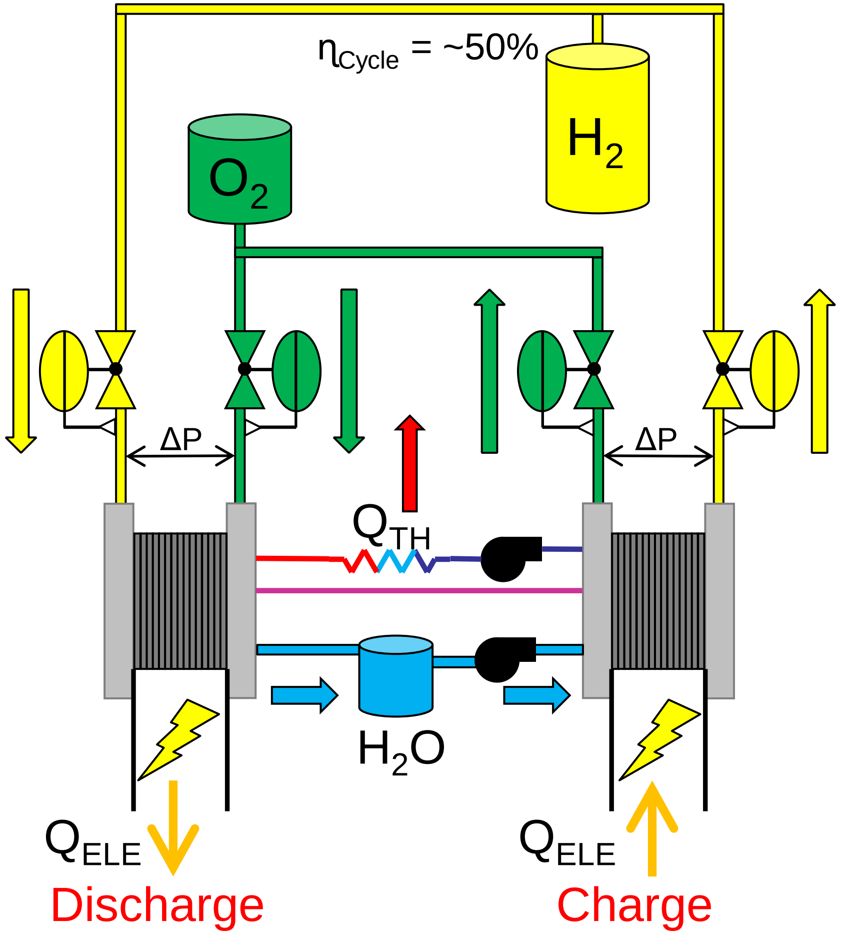
Regenerative fuel cells (RFCs) store energy remotely from the energy conversion mechanisms

- 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

Regenerative Fuel Cell Systems

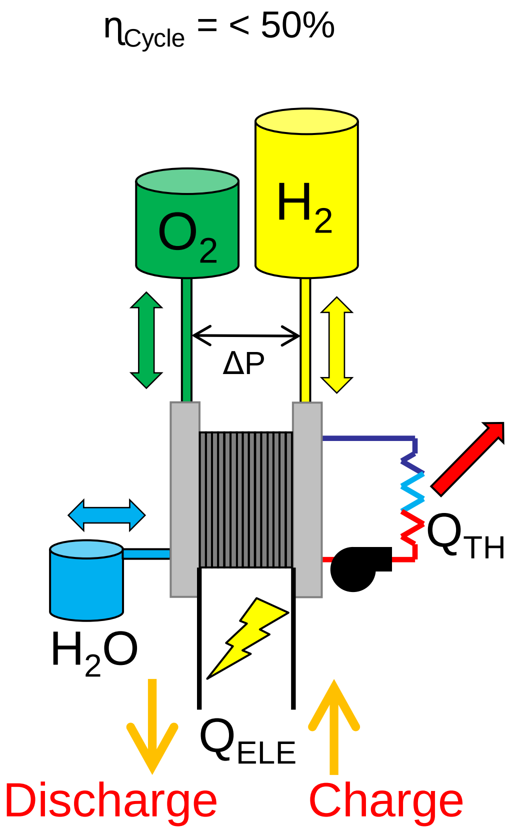
Discrete RFC

Optimized Processes



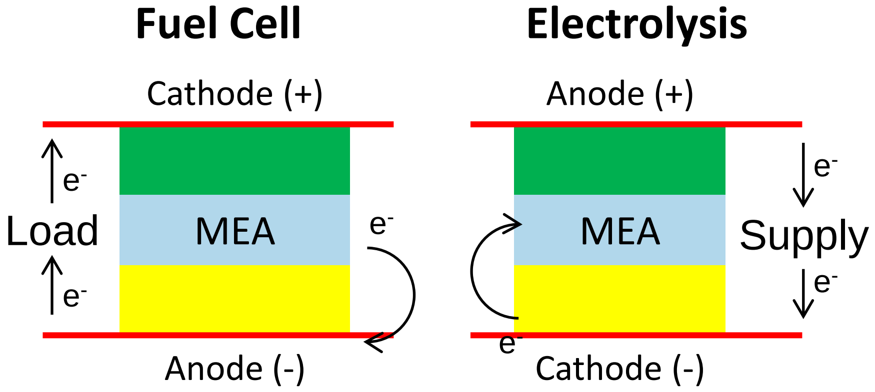
Unitized RFC

Hybrid Processes



Constant Gas

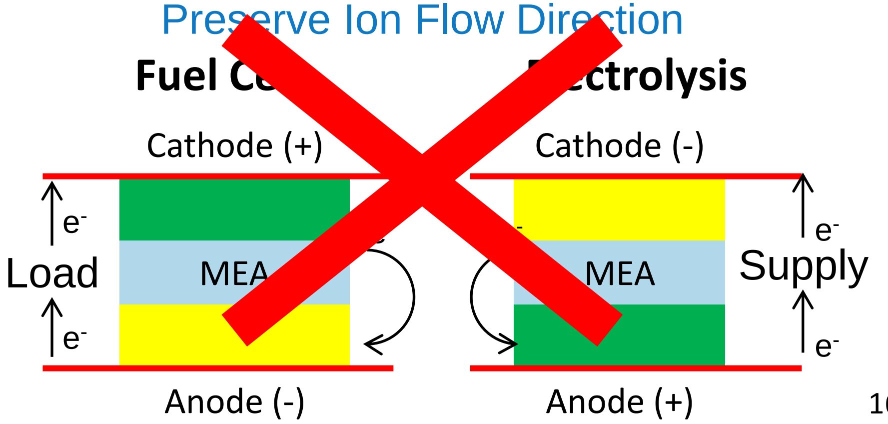
Change Ion Flow Direction



Currently not viable for crewed missions

Constant Electrode

Preserve Ion Flow Direction

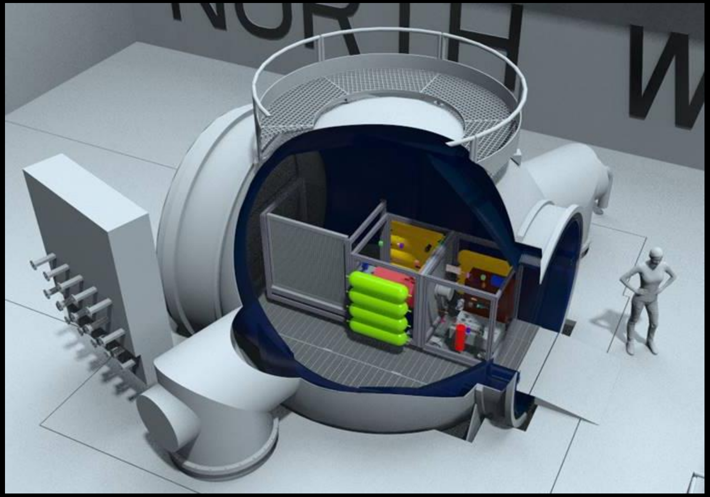


Space Fuel Cell Energy Storage Development Activities

PEM (Nafion-based)

TRL 3

1. TRL Advancement:
   System TRL Target = 5^+
   - Regenerative Fuel Cell Project
     - Low-Altitude Thermal Testing
     - Thermal-Vacuum Testing



Integrated RFC Test Article in JSC Energy Systems Test Area (ESTA) Thermal Vacuum Chamber

Alkaline

TRL 2 to 3

3. TRL Advancement:
   Component TRL Target = 5^+
   - Advanced Alkaline Reversible Cell (AARC) – pH Matter
   - Bifurcated Reversible Alkaline Cell for Energy Storage (BRACES) – pH Matter

Solid Oxide

TRL 2 to 3

1. TRL Advancement:
   Component TRL Target = 3 to 4
   - 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

Funding Sources

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Regenerative Fuel Cell Project Overview

Project Objective

Advance Regenerative Fuel Cell (RFC) technology from TRL 3 to at least TRL 5 by ground testing a fully integrated automatic RFC system in a simulated lunar environment

Technology Demonstration

- Verify system by continuously operating for ≥ 1 Lunar day/night cycle (>732 hours) powering a to-be-determined mission power profile from within a thermal-vacuum chamber (-173ºC to +105ºC, < 10^{-5} Torr)
- Hardware: Nominal 100 W_e class RFC system design extensible to ~ 7kW
  - Net Energy Storage = 36 kW·hrs (Objective)
  - Specific Energy (Calculated): Threshhold ≥ 320 W·hrs/kg Objective = 500 W·hrs/kg
  - Power Levels: Discharge Power = 0 to 400 Watts Charging Power = 0 to 1200 Watts
- Conduct a hardware life test of an RFC system to identify technology durability gaps

Deliverables

- Final report
  - Hardware Environmental Test Reports (Temperature, Pressure)
  - Hardware Life Test Report
  - Technology Development Gaps
  - Initial Requirements for a follow-on space flight RFC system

Develop RFC System Requirements

↓

Design & Build RFC Systems

↓

≥ 2 month autonomous closed-loop test under laboratory conditions

↓ Surface RFC TRL 4

≥ 2 month autonomous closed-loop test in a Relevant Environment

↓ Surface RFC TRL 5

Define parameters for Lunar Flight Demonstrator

↓

RFC for Surface Power

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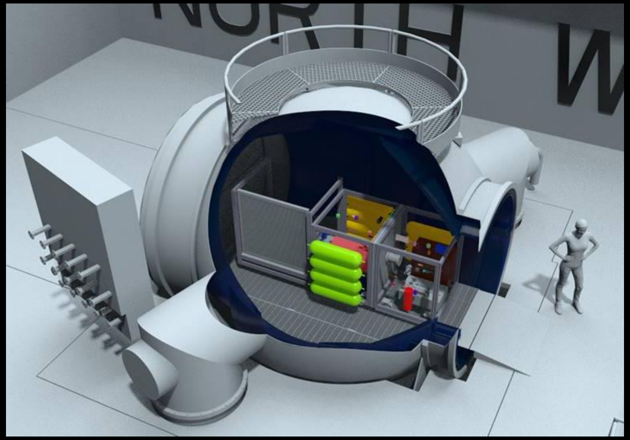

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Questions can be sent via e-mail to

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Thank you for your attention.