Fuel Cell Research and Development for Earth and Space Applications

Ian Jakupca,
NASA Glenn Research Center
17 July 2018
Presentation Outline

• NASA – Overview and Scope
• Background
  • Power and Energy Systems
  • Applicable Types of Electrochemical Systems
  • Energy Storage: Batteries vs. Regenerative Fuel Cells (RFC)
  • Comparison of Fuel Cell Technologies: Aerospace vs. Terrestrial
• Active NASA Fuel Cell research
  • Power Generation
  • Energy Storage
  • Commodity Generation
• Review
# NASA Exploration Campaign

## Notional Launches

### Early Science & Technology Initiative
- SMD—Pristine Apollo Sample, Virtual Institute
- HEO/SMD—Lunar CubeSats
- SMD/HEO—Science & Technology Payloads

### Small Commercial Lander Initiative
- HEO—Lunar Catalyst & Tipping Point
- SMD/HEO—Small Commercial Landers/Payloads

### Mid to Large Lander Initiative Toward Human-rated Lander
- HEO/SMD—Mid-sized Landers (~500kg–1000kg)
- HEO/SMD—Human Descent Module Lander (5–6000kg)
- SMD/HEO—Payloads & Technology/Mobility & Sample Return
- SMD—Mars Robotics

### Lunar Orbital Platform—Gateway
- HEO—Orion/SLS (Habitation Elements/Systems)
- HEO/SMD—Gateway Elements (PPE, Commercial Logistics)/Crew Support of Lunar Missions
- HEO/SMD—Lunar Sample Return Support

<table>
<thead>
<tr>
<th>Year</th>
<th>2018</th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
</tr>
</thead>
</table>

Timelines are tentative and will be developed further in FY 2019
The average temperature on the Moon (at the equator and mid latitudes) varies from 90 Kelvin (-298 degrees Fahrenheit or -183 degrees Celsius), at night, to 379 Kelvin (224 degrees Fahrenheit or 106 degrees Celsius) 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 degrees Fahrenheit or -238 degrees Celsius) 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
# Power and Energy Systems

## Power Generation
**Discharge Power Only**

**Description**
- Energy conversion system that supplies electricity to customer system
- Operation limited by initial stored energy

**Examples**
- Nuclear (e.g. RTG, KiloPower)
- Primary Batteries
- Primary Fuel Cells
- Photovoltaics

**NASA Applications:**
- Missions without access to continuous power (e.g. PV)
- All NASA applications require electrical power
- Each primary power solution fits a particular suite of NASA missions

## Energy Storage
**Charge + Store + Discharge**

**Description**
- Stores excess energy for later use
- Supplies power when baseline power supply (e.g. PV) is no longer available
- Tied to external energy source

**Examples**
- Rechargeable Batteries
- Regenerative Fuel Cells

**NASA Applications:**
- Ensuring Continuous Power
- Satellites (PV + Battery)
- ISS (PV + Battery)
- Surface Systems (exploration platforms, ISRU, crewed)
- Platforms to *survive* Lunar Night
# Summary of Applicable Electrochemical Chemistries

<table>
<thead>
<tr>
<th>Cell Type</th>
<th>Low Temperature</th>
<th>Moderate Temperature</th>
<th>High Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Proton Exchange Membrane (PEM)</strong></td>
<td>10 – 80 °C</td>
<td>70 – 225 °C</td>
<td>~650 °C</td>
</tr>
<tr>
<td><strong>Alkaline (AEM)</strong></td>
<td>20 – 70 °C</td>
<td>200 – 250 °C</td>
<td>600 – 1,000 °C</td>
</tr>
<tr>
<td><strong>Ionic Polymer Membrane</strong></td>
<td>H⁺</td>
<td>OH⁻</td>
<td>CO₃²⁻</td>
</tr>
<tr>
<td><strong>Alkaline Polymer Membrane</strong></td>
<td>OH⁻</td>
<td>H⁺</td>
<td>O²⁻</td>
</tr>
<tr>
<td><strong>KOH in asbestos matrix</strong></td>
<td>Phosphoric Acid in SiC structure</td>
<td>Liquid carbonate in LiAlO₂ structure</td>
<td>Anionic Conducting Ceramic</td>
</tr>
<tr>
<td><strong>Operating Temperature</strong></td>
<td>10 – 80 °C</td>
<td>20 – 70 °C</td>
<td>70 – 225 °C</td>
</tr>
<tr>
<td><strong>Charge Carrier</strong></td>
<td>H⁺</td>
<td>OH⁻</td>
<td>H⁺</td>
</tr>
<tr>
<td><strong>Load Slew Rate Capability</strong></td>
<td>Very High (&gt; 1k’s mA/cm²/s)</td>
<td>High (~ 1k’s mA/cm²/s)</td>
<td>High (~ 1k’s mA/cm²/s)</td>
</tr>
<tr>
<td><strong>Fuel</strong></td>
<td>Pure H₂</td>
<td>H₂, CO, Short Hydrocarbons</td>
<td>H₂, Oxygen, Hydrogen</td>
</tr>
<tr>
<td><strong>Product Water Cavity</strong></td>
<td>Oxygen</td>
<td>Hydrogen</td>
<td>Vapor, externally separated</td>
</tr>
<tr>
<td><strong>Product Water</strong></td>
<td>Liquid Product</td>
<td>Liquid Product</td>
<td>Liquid Product</td>
</tr>
<tr>
<td><strong>CO Tolerance</strong></td>
<td>&lt; 2 ppm</td>
<td>&lt; 2 ppm</td>
<td>&lt; 5 ppm</td>
</tr>
<tr>
<td><strong>Reformer Complexity</strong></td>
<td>Very High</td>
<td>High</td>
<td>Minimal</td>
</tr>
<tr>
<td><strong>Aerospace Viability</strong></td>
<td>Promising</td>
<td>TBR (Low TRL)</td>
<td>Not Viable</td>
</tr>
<tr>
<td><strong>Terrestrial Availability</strong></td>
<td>High (Increasing)</td>
<td>Developmental (Increasing)</td>
<td>Moderate (Stable)</td>
</tr>
<tr>
<td><strong>Terrestrial Markets</strong></td>
<td>Transportation, Logistics, Stationary Power (C, I, &amp; R)</td>
<td>Transportation, Logistics (C)</td>
<td>Co-generation and Stationary Power (C &amp; I)</td>
</tr>
</tbody>
</table>

Feasible for Aerospace Applications

- **Fuel Pure H₂**
- **Oxygen**
- **Hydrogen**
- **Liquid Product**
- **< 2 ppm**
- **< 2 ppm**
- **< 5 ppm**
- **Minimal**
- **Promising**
- **Moderate (Increasing)**
- **High (Increasing)**

---

**Legend:**
- C = Commercial
- I = Industrial
- R = Residential

---

**Source:** NASA
## Summary of Applicable Electrochemical Chemistries

<table>
<thead>
<tr>
<th>Key Notes</th>
<th>PEM</th>
<th>AEM</th>
<th>Alkaline</th>
<th>Solid Oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Commonly used in mobile terrestrial applications</strong></td>
<td>• Solid polymer electrolyte</td>
<td>• Reaction kinetics support transient load response capability</td>
<td>• Liquid electrolyte suspended in asbestos structure</td>
<td>• Commonly used in stationary terrestrial applications</td>
</tr>
<tr>
<td><strong>Terrestrial systems vent Oxygen to remove product water from stack</strong></td>
<td>• Developing technology not yet deployed</td>
<td>• Relatively high tolerance to contaminant gases</td>
<td>• Hydrogen recirculates to remove product water from stack</td>
<td>• Terrestrial systems vent hydrogen to remove product water from stack</td>
</tr>
<tr>
<td><strong>Mature for terrestrial applications, needs development for Aerospace</strong></td>
<td></td>
<td>• Solid polymer eliminates migration of corrosive electrolyte</td>
<td>• Used in Space Shuttle</td>
<td>• Mature for terrestrial applications, needs development for Aerospace</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Advantages</th>
<th>PEM</th>
<th>AEM</th>
<th>Alkaline</th>
<th>Solid Oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rapid reaction kinetics support transient load response capability</strong></td>
<td>• Reaction kinetics support transient load response capability</td>
<td>• Reaction kinetics support transient load response capability</td>
<td>• Reaction kinetics support transient load response capability</td>
<td>• Wide range of fuels (Anode)</td>
</tr>
<tr>
<td><strong>Support wide range of current densities</strong></td>
<td>• Relatively high tolerance to contaminant gases</td>
<td>• Relatively high tolerance to contaminant gases</td>
<td>• Relatively high tolerance to contaminant gases in Hydrogen</td>
<td>• Can be configured to internally reform hydrocarbons</td>
</tr>
<tr>
<td><strong>Minimal start times (typ. &lt; 1 min)</strong></td>
<td>• Solid polymer eliminates migration of corrosive electrolyte</td>
<td>• Higher pH enables larger selection for wetted materials</td>
<td>• Higher pH enables larger selection for wetted materials</td>
<td>• Relatively high tolerance to contaminant gases in Hydrogen</td>
</tr>
<tr>
<td><strong>Demonstrated high pressure operation</strong></td>
<td>• Higher pH enables larger selection for wetted materials</td>
<td></td>
<td></td>
<td>• Resistant to freezing when stored</td>
</tr>
<tr>
<td><strong>Solid polymer electrolyte eliminates migration of acidic electrolyte</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Disadvantages</th>
<th>PEM</th>
<th>AEM</th>
<th>Alkaline</th>
<th>Solid Oxide</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Very sensitive to CO or Sulfur contaminants in Hydrogen stream</strong></td>
<td>• Limited operational life</td>
<td>• No longer available as company divested both IP and fabrication capability</td>
<td>• Ceramic electrolyte limits transient load response capability</td>
<td>• Ceramic electrolyte limits start-up times to 10’s of minutes to hours</td>
</tr>
<tr>
<td><strong>Water-based system limits temperature regimes</strong></td>
<td>• Limited pressure capability</td>
<td>• EPA restricted use of asbestos</td>
<td>• Ceramic electrolyte limits start-up times to 10’s of minutes to hours</td>
<td>• Seals need development for Aerospace applications</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Liquid electrolyte migrates throughout fluid system requiring frequent and expensive servicing</td>
<td>• Limited to low-pressure applications</td>
<td></td>
</tr>
</tbody>
</table>
Aerospace Electrochemical Systems

**Fuel Cell**
- **Power Generation**
- 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-intensive 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**
- Description:
  - Converts chemical feedstock into useful commodities
  - Tied to external energy source
- **NASA Applications:**
  - Life-support, ISRU
  - Oxygen Generation
  - Propellant Generation
  - Material Processing

Chemical Equations:
- $2 \text{H}_2\text{O} \rightarrow 2 \text{H}_2 + \text{O}_2$
- or
- $2 \text{CO}_2 \rightarrow 2 \text{CO} + \text{O}_2$
Example $\text{H}_2/\text{O}_2$ Aerospace Fuel Cell Systems

**Fuel Cell**
- Power Generation
- $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O} + 4\text{e}^- + \text{Heat}$

**Regenerative Fuel Cell**
- Energy Storage
- $n_{\text{Cycle}} = \sim 50\%$

**Electrolysis**
- Commodity Generation
- $2\text{H}_2\text{O} + 4\text{e}^- \rightarrow 2\text{H}_2 + \text{O}_2 + \text{Heat}$

Regenerative Fuel Cell = Fuel Cell + Interconnecting Fluidic System + Electrolysis
Definitions: Power and Energy System Metrics

**Fuel Cell**
Power Generation

**Primary Metrics**
- Specific Power (W/kg)
- Output Power (Watts)
- Mass (kg)
- Volume (L)
- Reliability (Hours/Days)

**Technical Challenges**
- Water Management
- Reactant Purity
- Thermal Control
- Con-Ops
- Shelf-life

**Regenerative Fuel Cell**
Energy Storage

**Primary Metrics**
- Specific Energy (W•hrs/kg)
- Reliability (Years)
- Stored Energy (kW•hrs)
- Mass (kg)
- Volume (L)

**Technical Challenges**
- Component Reliability
- Corrosion/Chemical Compatibility
- Reactant Purity
- Water Management
- Con-Ops
- Thermal
- EZ System Pressure
- Maintenance
- Shelf-life

**Electrolysis**
Commodity Generation

**Primary Metrics**
- Production Rate (kg/day)
- Reliability (Months/Years)
- System Pressure (Atm)
- Mass (kg)
- Volume (L)

**Technical Challenges**
- System Pressure
- Component Reliability
- Corrosion/Chemical Compatibility
- Fluid Purity
- Con-Ops
- Maintenance
Comparison of Fuel Cell Technologies

Aerospace

- Space Shuttle Fuel Cell Stack (1979 - 2014)

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

Terrestrial

- Toyota Mirai Fuel Cell

  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
## Cross-Cutting Technologies: Fuel Cells, Electrolyzers, and RFCs

### Electrolyzer Technology
- **Electrochemistry**: TRL 9, High portability, High challenge
- **Materials**: TRL 5+, High portability, High challenge
- **Seals**: TRL 5+, High portability, High challenge
- **Gas Management**: TRL 5+, Moderate portability, High challenge
- **Flow Fields**: TRL 5+, High portability, High challenge
- **Bipolar Plates**: TRL 5+, Moderate portability, High challenge
- **Electrochemistry**: TRL 5+, Low portability, High challenge
- **Water Management**: TRL 5+, Low portability, High challenge
- **Fluidic Components**: TRL 8+, Moderate portability, High challenge
- **Procedures**: TRL 5, Moderate portability, High challenge
- **Thermal**: TRL 8+, Moderate portability, High challenge
- **Materials**: TRL 8+, Low portability, High challenge
- **Water Management**: TRL 5+, Low portability, High challenge
- **Hardware/PCB**: TRL 8+, High portability, High challenge
- **Power Management**: TRL 8+, High portability, High challenge
- **Structure**: TRL 8+, High portability, High challenge
- **Thermal**: TRL 8+, High portability, High challenge
- **Instrumentation**: TRL 8+, Moderate portability, High challenge

### Fuel Cell Technology
- **Reactant Storage and Management**:
  - **Electrochemistry**: TRL 5, Moderate portability, High challenge, O₂ vs air
  - **Materials**: TRL 5, Moderate portability, High challenge, O₂ vs air
  - **Gas Management**: TRL 5, Moderate portability, High challenge
  - **Flow Fields**: TRL 5, Moderate portability, High challenge
  - **Bipolar Plates**: TRL 5, Moderate portability, High challenge
  - **Electrochemistry**: TRL 5, Low portability, High challenge
  - **Water Management**: TRL 5, Low portability, High challenge
  - **Fluidic Components**: TRL 8, Moderate portability, High challenge
  - **Procedures**: TRL 5, Moderate portability, High challenge, O₂ vs air, Performance
  - **Thermal**: TRL 8, Moderate portability, High challenge, µg, Vacuum
  - **Materials**: TRL 8, Low portability, High challenge
  - **Water Management**: TRL 5, Low portability, High challenge
  - **Hardware/PCB**: TRL 8, High portability, High challenge
  - **Power Management**: TRL 8, High portability, High challenge
  - **Structure**: TRL 8, High portability, High challenge
  - **Thermal**: TRL 8, High portability, High challenge
  - **Instrumentation**: TRL 8, Moderate portability, High challenge

### System Avionics
- **NOTE**: Not all relevant technologies exist within the same application. Elements of multiple terrestrial applications are required to meet various NASA mission requirements.
RFC systems, along with their core fuel cell and water electrolyzer technologies, share common reactants (hydrogen, oxygen, water) with multiple subsystems while supporting an electrical power interface.
NASA Fuel Cell Applications
Powering exploration activities

- **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 Fuel Cell Applications
Powering exploration activities

• **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)
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 O₂/CH₄
• 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).

POC: Nicholas Borer, nicholas.k.borer@nasa.gov
Energy Storage Options for 300 W_{ele} Lunar Surface System By Location

<table>
<thead>
<tr>
<th>Lunar Site</th>
<th>Shaded Period</th>
<th>Energy Storage</th>
<th>Li-ion Mass</th>
<th>LRFC Mass</th>
<th>$ Savings @ $1.5 M/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Pole</td>
<td>73 hours</td>
<td>22 kW•hrs</td>
<td>137 kg</td>
<td>40 kg</td>
<td>$145.5</td>
</tr>
<tr>
<td>Equator</td>
<td>356 days</td>
<td>107 kW•hrs</td>
<td>668 kg</td>
<td>194 kg</td>
<td>$711</td>
</tr>
<tr>
<td>Lacus Mortis (45° N)</td>
<td>362 days</td>
<td>109 kW•hrs</td>
<td>679 kg</td>
<td>197 kg</td>
<td>$723</td>
</tr>
</tbody>
</table>
Energy Storage: Regenerative Fuel Cell System

### Reactant Storage

<table>
<thead>
<tr>
<th>Low-pressure Storage (100 psi)</th>
<th>High-pressure Storage (1,000 psi)</th>
<th>Cryogenic Storage</th>
<th>Shared with Propellant</th>
<th>Dedicated Propellant</th>
</tr>
</thead>
<tbody>
<tr>
<td>Long Life/Performance</td>
<td>Total</td>
<td>Rank</td>
<td>Total</td>
<td>Rank</td>
</tr>
<tr>
<td>0.9</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
<td>0.20</td>
</tr>
<tr>
<td>Longevity (&gt;10,000 hour run time)</td>
<td>0.9</td>
<td>2.5</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>0.9</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
<td>0.20</td>
</tr>
<tr>
<td>Stack's Vibration Tolerance</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>0.9</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
<td>0.20</td>
</tr>
<tr>
<td>Reversible Storage</td>
<td>4.50</td>
<td>0.9</td>
<td>1.00</td>
<td>0.20</td>
</tr>
</tbody>
</table>

### Water System Processing

<table>
<thead>
<tr>
<th>Reaction Storage/Thermal Balance</th>
<th>Passive/Thermal Rejection</th>
<th>Active Thermal Rejection</th>
<th>Nitration/Particulate Separation</th>
<th>清爽/Thermal Storage</th>
<th>RFC Reactor/Thermal Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
</tr>
<tr>
<td>Stack Longevity (&gt;50,000 hour run time)</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>0.9</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
</tr>
<tr>
<td>Stack Longevity (&gt;50,000 hour run time)</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
</tbody>
</table>

### Integrated System

<table>
<thead>
<tr>
<th>Electrolysis</th>
<th>PEM - Anode Feed</th>
<th>PEM - Cathode</th>
<th>PEM - Static</th>
<th>PEM - SOFC</th>
<th>PEM - SOFC-CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
</tr>
<tr>
<td>Shock/Vibration</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Thermal Cycle Durability (%)</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Reliability</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>0.9</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
</tr>
<tr>
<td>System Mass</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
<td>2.7</td>
</tr>
</tbody>
</table>

### Fuel Cells

<table>
<thead>
<tr>
<th>PEM-C - NfT</th>
<th>PEM-C - PFT</th>
<th>PEM-C - SOFC</th>
<th>PEM-C - SOFC-CO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.9</td>
<td>1.00</td>
<td>0.20</td>
<td>1.00</td>
</tr>
<tr>
<td>Active Thermal</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Low-Temperature Operation</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Passive Thermal</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>Rapid Startup</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
</tr>
<tr>
<td>System Mass</td>
<td>0.9</td>
<td>2.7</td>
<td>2.7</td>
</tr>
</tbody>
</table>

### Total Score (5.7.2 possible)

### Evaluation Factor Ranking

1. Mature Technology with heritage
2. Successful Field Deployment
3. Successful Laboratory Demonstrations
4. Not Applicable
5. Unproven Solution Available
6. Significant Development Required
7. Major Advancement Required
8. Probabilistic / Not Possible

*Reversible process (Fuel Cell/Electrolysis)
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

<table>
<thead>
<tr>
<th>Reactants</th>
<th>Volume (m(^3))</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Everything else</td>
<td>Everything else</td>
<td>Reactants</td>
</tr>
</tbody>
</table>
### Energy Storage: Regenerative Fuel Cell System

<table>
<thead>
<tr>
<th>Category</th>
<th>Element</th>
<th>Relative Maturity</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrochemical</td>
<td>PEM: Electrolysis</td>
<td>Advanced</td>
<td>ISS has flown but with major servicing requirements (every 201 days) and low pressure</td>
</tr>
<tr>
<td></td>
<td>PEM: Fuel Cell</td>
<td>Medium</td>
<td>Terrestrial hardware available but no Flight qualified hardware exists</td>
</tr>
<tr>
<td></td>
<td>Solid Oxide: Electrolysis</td>
<td>Low</td>
<td>MOXIE promising but existing leak rates challenging for H₂/H₂O/O₂, RFC application. Seal and pressure impose severe limitations for RFC application. Increasing scale a major concern. Limited CO/CO₂ life data available</td>
</tr>
<tr>
<td></td>
<td>Solid Oxide: Fuel Cell</td>
<td>Low</td>
<td>Terrestrial hardware available but has unacceptable seal and pressure issues for an Aerospace application. Increasing scale a major concern. Limited CO/CO₂ life data available</td>
</tr>
<tr>
<td>Reactant Management</td>
<td>Storage</td>
<td>Mature</td>
<td>Many examples of fluid storage flight hardware</td>
</tr>
<tr>
<td></td>
<td>Fluid Management</td>
<td>Medium</td>
<td>Life, durability, and reliability issues for components and system</td>
</tr>
<tr>
<td></td>
<td>Reactants</td>
<td>Medium</td>
<td>Material Compatibility and contamination issues over projected mission duration. Purity and freezing issues over projected mission duration. Most ECLSS solutions not applicable to RFC application</td>
</tr>
<tr>
<td></td>
<td>Water Management</td>
<td>Low</td>
<td>Purity and freezing issues over projected mission duration. Most ECLSS solutions not applicable to RFC application</td>
</tr>
<tr>
<td>PMAD</td>
<td>Control</td>
<td>Medium</td>
<td>New bus voltage and new operating environment require new designs and test programs</td>
</tr>
<tr>
<td></td>
<td>System</td>
<td>Medium</td>
<td>Thermal and electrical insulation/grounding at new power levels</td>
</tr>
<tr>
<td>Thermal</td>
<td>Deployment</td>
<td>Medium</td>
<td>Surface deployment options not yet demonstrated at scale required by RFC</td>
</tr>
<tr>
<td></td>
<td>Surfaces</td>
<td>Medium</td>
<td>Maintaining radiative surface not demonstrated in relevant environment at scale without servicing</td>
</tr>
<tr>
<td>System</td>
<td>ConOps</td>
<td>Low</td>
<td>Demonstrated RFCs require prohibitive maintenance schedules subject to a range of operational methodologies</td>
</tr>
<tr>
<td></td>
<td>Reliability / Life</td>
<td>Very Low</td>
<td>Limited life data available in relevant environment except for computer (CPU)</td>
</tr>
<tr>
<td></td>
<td>Instrumentation</td>
<td>Low</td>
<td>Calibration drift and durability are mission-limiting issues</td>
</tr>
</tbody>
</table>
Commodity Generation: Oxygen

- **Mars Oxygen In-Situ Resource Utilization Experiment (MOXIE)**
  - Flight demonstration experiment as a part of the Mars 2020 rover mission
  - Generates $\text{gO}_2$ from $\text{CO}_2$ 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 $\text{gO}_2$ by FY24
  - Evaluating existing system modifications to maintain mass while increasing generation pressure
  - Investigations into conserving $\text{gH}_2$ by-product
Commodity Generation: Hydrocarbon Fuel Synthesis

A Green Energy Application for SOE Co-Electrolysis:
Manufacture of synthetic fuels from captured CO$_2$ and renewable energy

- Combined CO$_2$ and H$_2$O electrolysis produces CO and H$_2$, a basic feedstock in the chemical industry (referred to as synthesis gas, or “syngas”)
- Syngas can be utilized to produce a wide variety of liquid hydrocarbons via the Fischer-Tropsch (F-T) process.
  - F-T process is a mature technology presently used to manufacture synthetic lubricants, etc.
  - Sasol (South Africa) produces gasoline and diesel fuel on a large scale via F-T.
- Recent review paper trade study concluded that synthetic gasoline could be produced for costs as low as $2/gal.*
- Allows the “recycling” of atmospheric CO$_2$ while maintaining our present hydrocarbon fuel infrastructure.

Two possible CO$_2$-recycling scenarios:
(a) CO$_2$ recycled from industrial plant emissions (potential to reduce CO$_2$ net emissions by 50%).
(b) Closed loop carbon recycling via CO$_2$ capture from Earth’s atmosphere (near-zero net emissions).

* Study and above graphic from Graves et al., Renewable and Sustainable Energy Reviews, 15, (2011) 1-23.
In-Space Manufacturing logo created through Freelancer crowd-sourced challenge.

Issued new appendix to NextSTEP Broad Agency Announcement soliciting proposals for development of first-generation, in-space, multi-material fabrication laboratory, or FabLab, for space missions.

First student-designed 3-D tool printed aboard station in 2016.

3-D printer installed on International Space Station in 2014. Crews aboard station have successfully used the printer to manufacture parts and tools on-demand.
NASA Fuel Cell Applications
Powering exploration activities

- Electrified Aircraft
  - Primary Power

- Landers
  - Primary Power

- Lunar Outposts
  - Energy Storage

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

- Lunar Orbital Platform - Gateway
- PPE - Habitat - Airlock - Logistics

- Lunar Surface Mission

- Mars robotics exploration, technology development
Back-up Slides
EXPLORATION MISSION-1

The first uncrewed, integrated flight test of NASA's Deep Space Exploration Systems. The Orion spacecraft and Space Launch System rocket will launch from a modernized Kennedy spaceport.

Total distance traveled: 1.3 million miles – Mission duration: 25.5 days – Re-entry speed: 24,500 mph (Mach 32) – 13 CubeSats deployed
EXPLORATION MISSION-2

The first crewed, integrated flight test of NASA’s Deep Space Exploration System, the Orion spacecraft and Space Launch System launching from a modernized Kennedy Spaceport.

Low-Earth Orbit
100 nmi orbit for 2 revolutions for Orion solar array deploy and a system checkout; first Earth orbit takes 90 minutes to complete

Crew Module (CM) Entry Interface
CM enters the Earth’s atmosphere at 34,500 miles per hour (11 kilometers per second)

Enter Low-Earth Orbit
Exploration Upper Stage performs an Perigee Raise Maneuver putting the spacecraft into a circular 100 nmi orbit

Prepare for Entry, Descent, and Landing
Crew Module/Service Module separation, service module enters disposal orbit, crew module starts Earth entry

Orion High Earth Orbit
Orion performs one 24 hour orbit for system checkout of critical life support systems before committing crew to lunar trajectory

Orion Outbound Transit
4 day transit to the Moon, requires several attitude maneuvers and outbound trajectory corrections to align for lunar fly-by

Orion Lunar Flyby
4800 nmi past the far side of the Moon

EUS Trans Lunar Injection (TLI) Burn
EUS performs TLI to put EUS on heliocentric disposal trajectory independent of Orion and astronaut crew

Jettison Core Stage
Perform Core Stage engine shutdown, then Orion and Exploration Upper Stage (EUS) separates

Jettison Solid Rocket Boosters
4 astronauts - Total distance traveled: 1,090,320 km - Mission duration: 9 days – Re-entry speed 24,500 mph (Mach 32) – 9 metric ton Co-Manifested Payload deploy

Launch
Astronauts launch from Pad 39B at Kennedy Space Center in Orion propelled by the Space Launch System

Enter High Earth Orbit
Exploration Upper Stage (EUS) performs Apogee Raise Burn to put Orion in High Earth Orbit; second high Earth orbit takes 24 hours to complete

EUS Heliocentric Disposal
EUS enters a heliocentric disposal trajectory

Orion Trans Lunar Injection (TLI) Burn
Orion’s Orbital Maneuvering System (OMS) engine performs TLI to lift Orion out of High Earth Orbit and start Orion’s trans-lunar trajectory

Return Transit
4 day transit to the Earth, requires several attitude maneuvers and return trajectory corrections to align for Earth atmospheric re-entry

Exploration Upper Stage (EUS)/Orion Stage Separation
Astronauts remain with Orion

Splashedown and Crew Recovery
Crew Module splashdown and astronaut recovery onto waiting ship
Summary of Applicable Electrochemical Reactions

**Recombination**

**Fuel Cell Reaction**

<table>
<thead>
<tr>
<th>SOFC</th>
<th>AFC</th>
<th>PEMFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>O=</td>
<td>OH−</td>
<td>H+</td>
</tr>
<tr>
<td>H2O</td>
<td>H2O</td>
<td>H2O</td>
</tr>
</tbody>
</table>

**Electrolysis**

<table>
<thead>
<tr>
<th>PEMEZ</th>
<th>AEZ</th>
<th>SOE</th>
</tr>
</thead>
<tbody>
<tr>
<td>O=</td>
<td>OH−</td>
<td>O=</td>
</tr>
<tr>
<td>H2O</td>
<td>H2O</td>
<td>H2O</td>
</tr>
</tbody>
</table>

**Load**

- 600 to 1,000 °C
- 20 to 225 °C
- 20 to 80 °C

**Supply**

- 20 to 80 °C
- 20 to 225 °C
- 600 to 1,000 °C

**Anode**

- e−
- +

**Cathode**

- e−
- −
Habitation Systems

Habitation Systems Elements

**LIFE SUPPORT**
- Excursions from Earth are possible with artificially produced breathing air, drinking water and other conditions for survival.
- NASA living spaces are designed with controls and integrity that ensure the comfort and safety of inhabitants.

**ENVIRONMENTAL MONITORING**
- Monitoring
  - O2 & N2
  - Moisture
  - Particles
  - Microbes
  - Chemicals
  - Sound
- Limited, crew-intensive onboard capability
- Reliance on sample return to Earth for analysis
- Limited, crew-intensive on-board capability
- Reliance on sample return to Earth for analysis

**CREW HEALTH**
- Astronauts are provided tools to perform successfully while preserving their well-being and long-term health.
- Bulky fitness equipment
- Limited medical capability
- Frequent food system resupply
- Smaller, efficient equipment
- Onboard medical capability
- Long-duration food system

**EVA: EXTRA-VEHICULAR ACTIVITY**
- Long-term exploration depends on the ability to physically investigate the unknown for resources and knowledge.
- Upper body high mobility for limited sizing range
- Construction and repair focused tools; excessive inventory of unique tools
- Full body mobility for expanded sizing range
- Geological sampling and surveying equipment; common generic tool kit
Throughout every mission, NASA is committed to minimizing critical risks to human safety. Sustainable living outside of Earth requires explorers to reduce, recycle, reuse, and repurpose materials. Powerful, efficient, and safe launch systems will protect and deliver crews and materials across new horizons. During each journey, radiation from the sun and other sources poses a significant threat to humans and spacecraft.
Lunar Architecture Studies identified regenerative fuel cells and rechargeable batteries as enabling technologies, where enabling technologies are defined as having: “overwhelming agreement that the program cannot proceed without them.”

**Surface Systems**

**Surface**
- Reliable, long-duration maintenance-free operation; human-safe operation; architecture compatibility; high specific-energy, high system efficiency.

**Mobility Systems**
- Reliable, safe, primary power from batteries and fuel cells, and energy storage from secondary batteries and regenerative fuel cells in small mass and volume. Human-safe operation; reliable, maintenance-free operation; architecture compatibility; high specific-power and high specific-energy.

**Lander**

**Descent Stage**
- Functional primary fuel cell with 3-kW nominal power, 6-kW peak power.
- Human-safe reliable operation; high energy-density; architecture compatibility (operate on residual propellants).