NASA Hydrogen and Fuel Cell Perspectives

John Cavolowsky
Director, Transformative Aeronautics Concept Program (TACP)
NASA Aeronautics Research Mission Directorate (ARMD)

Ian Jakupca
Fuel Cell Technology Lead
NASA Glenn Research Center

29 March 2022
Presentation Overview

• Provide a background of NASA Hydrogen activities technologies for Aerospace applications:
  o Reactant generation
    ❖ Environmental Control and Life Support (ECLSS)
    ❖ In Situ Resource Utilization (ISRU)
    ❖ Energy Storage / Hydrogen Economy
  o Reactant Transfer and Storage
    ❖ Cislunar propellant infrastructure
  o Power Generation / Energy Storage
    ❖ Primary Fuel Cells (Power)
    ❖ Regenerative Fuel Cells (Energy Storage)

Mars Oxygen ISRU Experiment (MOXIE) Aboard Perseverance, demonstrated the first production of oxygen from the atmosphere of Mars Apr. 2021.

Hydrogen Activities Within NASA

**Reactant Generation**
- Electrochemically dissociating water into gaseous hydrogen and oxygen
  - Environmental Control and Life Support Systems (ECLSS)
  - Energy Storage
  - ISRU
  - Contaminated Water Sources (ISRU)
- Recover raw materials from local sources
  - Water (ice) Mining
  - Contaminated Water Processing
  - Regolith Processing

**Transfer and Storage**
- Hydrogen Management
  - Cryogenic Fluid Transfer in μ-gravity
  - Cryogenic Storage and Transfer
- Extend storage duration of cryogenic fluids
  - Zero-Boil-off Tanks
  - High-efficiency Efficiency Cryo-coolers

**Power Production**
- Propellants
  - Launch Vehicles
  - Mars/Lunar Landers
- Fuel hydrogen-based fuel cells
  - Lunar/Mars surface systems
  - Urban Air Mobility
- Metal Processing
- Refrigerants

**Reactant Generation**
- Electrochemically dissociating water into gaseous hydrogen and oxygen
  - Environmental Control and Life Support Systems (ECLSS)
  - Energy Storage
  - ISRU
  - Contaminated Water Sources (ISRU)
- Recover raw materials from local sources
  - Water (ice) Mining
  - Contaminated Water Processing
  - Regolith Processing

**Transfer and Storage**
- Hydrogen Management
  - Cryogenic Fluid Transfer in μ-gravity
  - Cryogenic Storage and Transfer
- Extend storage duration of cryogenic fluids
  - Zero-Boil-off Tanks
  - High-efficiency Efficiency Cryo-coolers

**Power Production**
- Propellants
  - Launch Vehicles
  - Mars/Lunar Landers
- Fuel hydrogen-based fuel cells
  - Lunar/Mars surface systems
  - Urban Air Mobility
- Metal Processing
- Refrigerants
With their core fuel cell and water electrolyzer technologies, multiple electrochemical applications share common reactants and power/energy requirements.

**ECLSS** = Environmental Control and Life Support Systems  
**ISRU** = In Situ Resource Utilization  
**PMAD** = Power Management and Distribution  
**RFC** = Regenerative Fuel Cell  
**TRL** = Technology Readiness Level  
* = Application-Specific Technology Readiness Level

### Aerospace Electrochemistry Options

1) **Proton Exchange Membrane (PEM)**  
   - Low Temperature (-4 to 85 °C)  
   - Reactant Cycles  
     - H₂ / O₂ / H₂O  
     - TRL 5+ / 9*  
     - HT-PEM TRL 2*

2) **Solid Oxide**  
   - Reactant Cycles  
     - H₂ + O₂ ↔ H₂O  
     - (CH₄ + CO + H₂) + O₂ → H₂O + CO₂  
   - Anionic Conducting (O²⁻)  
   - Fuel cell mode TRL 3+  
     - (TRL 9 terrestrial)  
   - Electrolysis mode TRL 9*  
   - Protonic Conducting (H⁺) TRL 3

3) **Alkaline**  
   - Reactant Cycles  
     - H₂ + O₂ ↔ H₂O  
   - TRL 3+ (TRL 9 terrestrial)
Electrolysis
- Hydrogen production process for over 100 years
- **Green** technology if power source is renewable
- Fluidic analogy
  - Current ~ H₂ production rate
  - Voltage ~ H₂ 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

Requires Input Power
DC Current + Water → H₂ + ½ O₂ + Heat

Unit Cell Electrolysis Performance
- "Preferred" Operational Range
- **Input Power**
- Max Load
- Min Load
- Increasing Current
- Increasing Waste Heat to Dissipate
- **Electrical Potential, Volts**
- **Current Density, mA/cm²**
Reactant Generation

**Electrolysis**
- Electrochemically dissociate water into gaseous hydrogen and oxygen
- ECLSS
  - Unbalanced Design (H₂ << O₂)
  - Unmet long-term requirements for reliability, life, or H₂ sensors stability
- Energy Storage
  - Balance Design (H₂ ≈ O₂)
  - Unmet long-term requirements for performance, reliability, life, sensors availability, sensor stability
- ISRU
  - Balance Design (H₂ ≈ O₂)
  - Unmet long-term requirements for performance, reliability, or life
  - Tolerate contaminated water sources to minimize pre-conditioning requirements

**Water Mining and Processing**
- Recover raw materials from local sources
  - Regolith Processing
- 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. H₂S, NH₃, H₂CO₃, H₂SO₄, Hg, Methanol, etc.)
How Making Propellants on Planetary Surfaces Saves on Launches and Cost (Gear Ratio Effect)

Every 1 kg of propellant made on the Moon or Mars saves 7.5 to 11.2 kg in LEO

- Enable exploration by staging required resources in forward locations
  - Earth Orbit (LEO, GEO)
  - LaGrange Points (EML1 and EML2)
  - Lunar Orbit
  - Lunar Surface
- Resources include propellant depots, propellant production facilities (initially H₂ and O₂), and consumable storage

Potential >283 mT launch mass saved in LEO = 3+ SLS launches per Mars Ascent
- Savings depend on in-space transportation approach and assumptions; previous Mars gear ratio calculations showed only a 7.5 kg saving
- 25,000 kg mass savings from propellant production on Mars for ascent = 187,500 to 282,500 kg launched into LEO

Moon Lander: Surface to NRHO
- Crew Ascent Stage (1 way): 3 to 6 mT O₂
- Single Stage (both ways): 40 to 50 mT O₂/H₂

<table>
<thead>
<tr>
<th>A Kilogram of Mass Delivered Here...</th>
<th>...Adds This Much Initial Architecture Mass in LEO</th>
<th>...Adds This Much To the Launch Pad Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ground to LEO</td>
<td>-</td>
<td>20.4 kg</td>
</tr>
<tr>
<td>LEO to Lunar Orbit (r1→r2)</td>
<td>4.3 kg</td>
<td>87.7 kg</td>
</tr>
<tr>
<td>LEO to Lunar Surface (r1→r3, e.g., Descent Stage)</td>
<td>7.5 kg</td>
<td>153 kg</td>
</tr>
<tr>
<td>LEO to Lunar Orbit to Earth Surface (r1→r4→r5, e.g., Orion Crew Module)</td>
<td>9.0 kg</td>
<td>183.6 kg</td>
</tr>
<tr>
<td>Lunar Surface to Earth Surface (r3→r4, e.g., Lunar Sample)</td>
<td>12.0 kg</td>
<td>244.8 kg</td>
</tr>
<tr>
<td>LEO to Lunar Surface to Lunar Orbit (r1→r3→r4→r5, e.g., Ascent Stage)</td>
<td>14.7 kg</td>
<td>300 kg</td>
</tr>
<tr>
<td>LEO to Lunar Surface to Earth Surface (r1→r3→r4→r5, e.g., Crew)</td>
<td>19.4 kg</td>
<td>396.8 kg</td>
</tr>
</tbody>
</table>
ISRU Synergistic with Terrestrial Needs

- Improve water cleanup techniques
- Advance food/plant growth techniques and nutrient production

- Reduce or eliminate cement and asphalt – renewable materials
  - Alternative construction techniques – 3-D printing, no Portland cement
  - Remote operation and automation

- Increase safety
- Reduce maintenance and logistics
- Increase mining and processing efficiency
- Improve environmental compatibility

- More efficient power generation, storage and distribution
- Increase renewable energy: Use sun, thermal, trash, and alternative fuel production
- Reduction of Carbon Dioxide emissions

Promote **Reduction, Reuse, Recycle, Repair, Reclamation**
...for benefit of Earth, and living in Space.
Reactant Transfer and Storage

Transporting Hydrogen and Oxygen through cis-lunar space is very complicated

Variable Storage times
Supply vehicle can launch days to months before target vehicle

No buoyancy to help separate the cryogenic fluids from evolved gases
Complex multi-phase fluid flow

Complex Thermal Environment
Very low H\textsubscript{2} liquid transition temperatures

- Radiation only available heat sink
- Very large temperature differences between sun-facing and deep-space facing surfaces

- Challenging to pre-cool target system while retaining cryogenic fluids within the system
**Basic Electrochemical Systems: Fuel Cell**

**Fuel Cell**
- Primary electrical **current** source (voltage indicates conversion efficiency)
- Fluidic analogy
  - Fuel cell ~ fluid pump
  - Current ~ fluid flow rate
  - Voltage ~ fluid pressure
- Pure water byproduct (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
  - Balance of Plant between stack and storage impacted, but stack is not

**Discharge Power Only**

Fuel + Oxidizer → DC Current + Water + Heat

**Unit Cell Fuel Cell Performance**

Electrical Potential, Volts

Current Density, mA/cm\(^2\)

Power Density, W/cm\(^2\)

Min Load → “Preferred” Operational Range → Max Load

Increasing Current

Increasing Waste Heat to Dissipate
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

- **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

**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
**Power Generation and Storage**

**Propellants**
- NASA currently requires between 3 to 10 million pounds LH₂ per year but likely to increase with launch cadence
- KSC and SSC require 5 to 12 commercial tankers / day during LH₂ fill to minimize schedule impacts
- Space Launch Systems (SLS)
  - 539,000 gal LH₂ capacity
  - Burn rate is ≈67,375 gal LH₂/min
- Commercial Cis-Lunar Transportation industry estimated to need ≈50,000 to ≈275,000 kg LH₂/year

**Hydrogen-based fuel cells**
- Lunar/Mars surface systems
  - ≤10 kW primary fuel cell modules fueled by H₂/O₂ or CH₄/O₂
  - 36 kW·hrₙₑₙ to 1 MW·hrₙₑₙ energy storage using H₂/O₂ regenerative fuel cell systems
- Urban Air Mobility
  - Multiple air-based primary fuel cell systems studies for systems fueled by H₂, CH₄, and bio-fuels (e.g. X-57)
  - Hydrogen storage technologies for aircraft (e.g. CHEETAH)
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
  o Meet/exceed aviation goals for alternative propulsion and energy options
  o An aircraft system with a quiet, efficient propulsion system that produces zero CO₂, NOₓ, and particulate emissions

• Research associated technologies
  o Distributed aero-propulsion system integration
  o High-efficiency electrochemical power conversion
  o Flight-weight electric machines and power electronics,
  o Materials and systems for superconducting high-efficiency power transmission
  o Methods for complex system integration and optimization.
  o 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/)
Presentation Summary

• Provided a background of NASA Hydrogen activities technologies:
  o Reactant generation supporting
    ❖ Environmental Control and Life Support (ECLSS)
    ❖ In Situ Resource Utilization (ISRU)
    ❖ Energy Storage / Hydrogen Economy
  o Reactant Transfer and Storage
    ❖ Cis-lunar propellant infrastructure
  o Power Generation / Energy Storage
    ❖ Primary Fuel Cells (Power)
    ❖ Regenerative Fuel Cells (Energy Storage)

Mars Oxygen ISRU Experiment (MOXIE) Aboard Perseverance, demonstrated the first production of oxygen from the atmosphere of Mars Apr. 2021.

Questions can be sent via e-mail to
- John Cavolowsky (john.a.cavolowsky@nasa.gov)
- Ian Jakupca (ian.j.jakupca@nasa.gov)
Thank you for your attention.