NASA Fuel Cell and Hydrogen Research Activities

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Presented by:
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NASA Glenn Research Center
Presentation Overview

• Overview of NASA Hydrogen Requirements
• Aeronautic Applications
• Space Applications

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

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
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)
Fuel Cell Power Generation

Fuel cells provide primary direct current (DC) electrical power

- Use pure to propellant-grade $\text{O}_2 / \text{H}_2$ or $\text{O}_2 / \text{CH}_4$ 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

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

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**Electrolysis**

- Electrochemically dissociate water into gaseous hydrogen and oxygen
- ECLSS
  - Unbalanced Design ($H_2 \ll O_2$)
  - 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.)
**Power Generation and Storage**

- **Propellants**
  - Launch Vehicles
  - Mars/Lunar Landers

- **Fuel hydrogen-based fuel cells**
  - Lunar/Mars surface systems
  - Urban Air Mobility / Zero Emission

**Reactant Generation**

- Electrochemically dissociating water into gaseous hydrogen and oxygen
  - Environmental Control and Life Support Systems (ECLSS)
  - Energy Storage
  - In-Situ Resource Utilization (ISRU)
  - Contaminated Water Sources for ISRU

- **Recover raw materials from local sources**
  - Water (ice) Mining
  - Contaminated Water Processing
  - Regolith Processing

**Metal Processing**

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### Fuel Cell and Hydrogen Activities Within NASA

<table>
<thead>
<tr>
<th>Electrolyte Chemistry</th>
<th>Power</th>
<th>Electrolysis</th>
<th>Regenerative</th>
<th># Projects</th>
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<td>3</td>
<td>6</td>
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<tr>
<td>Proton Exchange Membrane (PEM)</td>
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<td>7</td>
<td>4</td>
<td>17</td>
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<td>Solid Oxide</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Other</td>
<td>3</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>12</td>
<td>14</td>
<td>7</td>
<td>33</td>
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</table>

Mars Oxygen ISRU Experiment (MOXIE)
Aboard Perseverance, demonstrated the first production of oxygen from the atmosphere of Mars Apr. 2021.
Aeronautics
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/)
Integrated Zero-Emission Aviation using a Robust Hybrid Architecture (IZEA)

The project goals and broader impacts can be summarized as:

• Figure out how to use liquid hydrogen as fuel
  o Burning hydrogen to produce electricity has water vapor as exhaust.
  o Solving challenges related to safety, engineering, electrical, thermal, infrastructure, and societal acceptance helps aviation.

• Increase power and efficiency without increasing weight
  o Liquid hydrogen is very cold (cryogenic), which enables using superconductors to greatly increase power density.
  o Fuel cells and electric motors provide cruise thrust instead of heavy batteries and turbofans.

• Research tasks
  o Evaluate the potential for global warming reduction across the passenger aviation fleet
  o Use a multi-disciplinary design, analysis and optimization approach to identify and model hydrogen-fueled aircraft for the fleet
  o Develop a feasible power generation and energy conversion subsystem
  o Develop a feasible power electronics, distribution and motor-driven propulsion subsystem
  o Develop a thermal management system to optimize efficiency

• Unify all tasks with real demonstrations on a system testbed

Principal Investigator: Lance Cooley
Lead Organization: Florida State University (FSU)
Supporting Organizations:
  • Advanced Magnet Lab, Inc. (AML)
  • Florida Agricultural and Mechanical University (FAMU)
  • Georgia Institute of Technology-Main Campus (GA Tech)
  • Illinois Institute of Technology
  • Raytheon Technologies Research Center
  • SUNY Buffalo State
  • The Boeing Company (Boeing)
  • University of Kentucky

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Sustainable Aviation Demo (Liquid Hydrogen Aircraft)

• Description
  – Develop smart buyer approach for gaps required for hydrogen aircraft development through the next few years
  – Focused on single aisle replacement aircraft for mid 2030s.

• Activities
  – Support Georgia Tech Conceptual design studies
  – Develop methodologies to size metallic and composite tanks
  – Develop concepts for improved insulation systems required to maintain hydrogen storage on aircraft.
  – Investigate concepts of operation for loading/distribution of hydrogen to aircraft
  – Support joint US/European hydrogen aircraft standards development with WSTF

• Significance
  – Find ways to help guide US aircraft industry as it explores development of liquid hydrogen aircraft.
  – Leverage space technologies and knowledge base as applicable

POC: Dave Koci (f.d.koci@nasa.gov)
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
Space
Do Terrestrial Systems apply to Aerospace Applications?

Answer: Sometimes

Fluid management issues and environmental conditions make aerospace and terrestrial fuel cells functionally dissimilar.

Aerospace

Differentiating Characteristics
- Pure Oxygen (stored, stoichiometric)
- Water Separation in $\mu$g

Terrestrial

Differentiating Characteristics
- Atmospheric Air (conditioned, excess flow)
- High air flow drives water removal
A SUSTAINED PRESENCE ON THE SURFACE

A steady cadence of missions and a robust infrastructure on the lunar surface

- An unpressurized rover provides extended exploration range and mobility for two suited crew on the lunar surface
- A pressurized rover expands exploration range
- A foundation surface habitat enables longer duration stays
- Supported with small logistics landers (e.g. CLPS)
- International partnerships
- Science, technology demonstrations, operational analogs for Mars missions
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
- Resources include propellant depots, propellant production facilities (initially $H_2$ and $O_2$), 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 $O_2$
- Single Stage (both ways): 40 to 50 mT $O_2/H_2$

A Kilogram of Mass Delivered Here...

<table>
<thead>
<tr>
<th></th>
<th>...Adds This Much Initial Architecture Mass in LEO</th>
<th>...Adds This Much To the Launch Pad Mass</th>
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</thead>
<tbody>
<tr>
<td>Ground to LEO</td>
<td>-</td>
<td>20.4 kg</td>
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<tr>
<td>LEO to Lunar Orbit</td>
<td>4.3 kg</td>
<td>87.7 kg</td>
</tr>
<tr>
<td>(1→2)</td>
<td></td>
<td></td>
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<tr>
<td>LEO to Lunar Surface</td>
<td>7.5 kg</td>
<td>153 kg</td>
</tr>
<tr>
<td>(1→3), e.g., Descent Stage</td>
<td></td>
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<tr>
<td>LEO to Lunar Orbit to Earth Surface</td>
<td>9.0 kg</td>
<td>183.6 kg</td>
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<tr>
<td>(1→4→5), e.g., Orion Crew Module</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lunar Surface to Earth Surface</td>
<td>12.0 kg</td>
<td>244.8 kg</td>
</tr>
<tr>
<td>(4→5), e.g., Lunar Sample</td>
<td></td>
<td></td>
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<tr>
<td>LEO to Lunar Surface to Lunar Orbit</td>
<td>14.7 kg</td>
<td>300 kg</td>
</tr>
<tr>
<td>(4→3→4), e.g., Ascent Stage</td>
<td></td>
<td></td>
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<tr>
<td>LEO to Lunar Surface to Earth Surface</td>
<td>19.4 kg</td>
<td>395.8 kg</td>
</tr>
<tr>
<td>(4→3→5), e.g., Crew</td>
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</table>
• NASA continues to pursue Lunar Exploration goals through the Human Landing System
  – Multiple risk reduction and development activities with regards to the long duration storage and transfer of liquid hydrogen in orbit

• The Space Technology Mission Directorate is pursuing multiple Tipping Point flight demonstrations:
  – Lockheed Martin, Cryogenic Demonstration Mission – storage and transfer of liquid hydrogen
  – United Launch Alliance – transfer of liquid hydrogen and liquid oxygen

• Continue the development of Radio Frequency Mass Gauge for mass gauging in unsettled conditions

• Hydrogen liquefaction for the Lunar and Martian surface – completed conceptual design trades
  – Demonstrated oxygen liquefaction techniques that partially apply to hydrogen

• Completed Testing of 20 W at 20 K cryocooler prototype for spaceflight applications

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**Key Performance Parameters for the 20 W/20 K RTB Cryocooler Project**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>State of the Art</th>
<th>Threshold Value</th>
<th>Project Goal</th>
<th>Tested Values¹</th>
<th>Projected Values²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Lift Capacity (W)</td>
<td>1</td>
<td>17</td>
<td>20</td>
<td>19.2</td>
<td>20.4</td>
</tr>
<tr>
<td>2) Specific Mass (kg/W)³</td>
<td>18.7</td>
<td>5.5</td>
<td>4.4</td>
<td>5.5</td>
<td>5.2</td>
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<tr>
<td>3) Specific Power (W/W)</td>
<td>370</td>
<td>80</td>
<td>60</td>
<td>91.6</td>
<td>86.3</td>
</tr>
</tbody>
</table>

**Notes:**

KPPs assume a fully integrated cryocooler operating and are based on a 20K design point, and do not include the mass and inefficiency of the drive electronics.

1. Tested values were only able to be achieved at a heat rejection temperature of 285K.
2. Projected values are based on data projections from a heat rejection temperature of 285K to 270K.
3. Specific mass values are based on flight-like projections.

POC: Wes Johnson (wesley.l.johnson@nasa.gov)
Space Fuel Cell Power Development Activities

**PEM (Nafion-based)**

1. Sub-orbital Flight Technology Demonstration
   - Advanced Modular Power and Energy System (AMPES) – Infinity Fuel Cell & Hydrogen
   - Hydrogen Electrical Power System (HEPS) – Teledyne

**Solid Oxide**

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

**Funding Sources**

- NASA Funds
- Tipping Point / ACO
- SBIR / STTR
Space Fuel Cell Electrolysis and Energy Storage Development Activities

**PEM (Nafion-based)**

1. Electrolysis Advancement: *Component*
   - Static Vapor Feed Electrolysis

2. Electrolysis Advancement: *System*
   - Advanced Oxygen Generator Assembly

3. Energy Storage Advancement: *System*
   - Regenerative Fuel Cell Project

**Alkaline**

1. Electrolysis Storage Advancement: *Component*
   - Advanced Alkaline Electrolyzer (AAE) – Teledyne

2. Energy Storage Advancement: *Component*
   - Advanced Alkaline Reversible Cell (AARC) – pH Matter
   - Bifurcated Reversible Alkaline Cell for Energy Storage (BRACES) – pH Matter

**Solid Oxide**

1. TRL Advancement: *Component*
   - Highly Efficient, Durable Regenerative Solid Oxide Stack - Precision Combustion
   - Efficient, High Power Density Hydrocarbon-Fueled Solid Oxide Stack System - Precision Combustion

**Funding Sources**

| NASA Funds | Tipping Point / ACO | SBIR / STTR |
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. Specific Energy
   - Increase system-level specific energy to increase vehicle payload capacity
Presentation Review

• Overview of NASA Hydrogen Requirements
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Credits: NASA Photo / Lauren Hughes
Questions
Thank you for your attention.