NASA Activities in Fuel Cell and Hydrogen Technologies

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Presentation Overview

• High Level Overview of fuel cell and electrolysis technologies
  o Cell, Cell Stack, Cell Stack Assembly
  o Types of Stacks
  o Types of Regenerative Fuel Cell Systems
  o Differences between Fuel Cells and Batteries

• Provide a background of NASA fuel cell and electrolysis activities technologies for Aerospace applications:
  o Reactant generation supporting Environmental Control and Life Support (ECLSS) and In Situ Resource Utilization (ISRU)
  o Reactant Transfer and Storage
  o Power and Energy Storage

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

Fuel Cell Powered Scarab Rover
Demonstrated field operation of H₂/O₂ fuel cell with a solar powered base of operations Aug. 2015.
Electrochemical Interoperability

With their core fuel cell and water electrolyzer technologies, multiple electrochemical applications share common reactants and power/energy requirements.

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)

Legend
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
Fluid management issues and environmental conditions make aerospace and terrestrial electrochemical systems functionally dissimilar.
Basic Fuel Cell and Electrolysis Reactions

• NASA utilizes the reversible oxidation-reduction reactions of hydrogen, oxygen, and water for multiple applications

\[ H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O \]

- Fuel Cell reaction releases energy
- Electrolysis reaction requires energy

• Multiple inefficiencies limit cyclic or “round-trip” efficiency to < 60%
Basic Electrochemical Stack

**Unit Cell**
Fundamental Working Unit

- Fuel In
- Oxidizer In

- Chemical Reaction Zone

- Fuel and Reaction Byproducts Out (Cell)
- Oxidizer and Reaction Byproducts Out (Cell)

1 cm

**Cell Stack**
“Filter-Press” Design

- Mechanical Compression

- Repeating Cell Units

- Low Temperature = Bipolar Plate
- High Temperature = Interconnect

- Not Shown: Fluid Manifolds connecting process fluids to each cell

**Cell Stack Assembly**
Base System Unit

- Fuel In
- Oxidizer In

- \( Q_{TH} \) Waste Heat

- Fuel and Reaction Byproducts Out (Stack)
- \( Q_{ELE} \) Oxidizer and Reaction Byproducts Out (Stack)
Basic Electrochemical Systems

**Fuel Cell Applications**
- Primary power
- RFC Discharge power
- Operational duration based on reactant storage

**Primary Fuel Cell**
**Discharge Power Only**

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

**Electrolysis**
**Chemical Conversion**

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

**Fuel Cell Performance**
- Decreasing Efficiency
- Increasing Current

**Electrolysis Cell Performance**
- Decreasing Efficiency
- Increasing Current

**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

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**Chemical Conversion**

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- ISRU Material Processing
Regenerative Fuel Cell = Fuel Cell + Interconnecting Fluidic System + Electrolysis
Regenerative Fuel Cell Systems

**Unitized RFC**

Energy Storage System

- Discharging
- Charging

\[ \Delta P \]

\[ Q_{ELE} \]

\[ Q_{TH} \]

- \( \eta_{Cycle} = < 50\% \)

Notes
- Very low TRL for space applications
- Operational pressure limited resulting in very large tanks or independent compression
- Limited by water management issues in low temperature chemistries
- Significant recent investment indicating some promise

**Discrete RFC**

Energy Storage System

- Discharging
- Charging

\[ \Delta P \]

\[ Q_{ELE} \]

- \( \eta_{Cycle} = \sim 50\% \)

Notes
- Potentially complicated water management
- Proof-of-concept demonstrations
  - Multiple chemistries
  - Aeronautic systems in flight configurations
  - Space systems in laboratory configurations
- Commercial H\(_2\)/air systems available
  - Uninterruptable Power Supply (kW·hr to GW·hr)
  - On-time performance primary requirement
  - No roundtrip or specific energy requirements

**Notes**

- Operational pressure limited resulting in very large tanks or independent compression
- Limited by water management issues in low temperature chemistries
- Significant recent investment indicating some promise
Unitized Regenerative Fuel Cells

**Constant Gas**  
Change Ion Flow Direction

**Fuel Cell**
- Cathode +  
- Load  
- Anode -  
- MEA

**Electrolysis**
- + Anode  
- Supply  
- - Cathode

**Advantages**
- Constant Gas Location
  - Simple Fluidic Systems
  - Fast mode transition times

**Disadvantages**
- Complex Power Electronics
  - Power Switching Required
  - Diode Protection Required

**Constant Electrode**  
Preserve Ion Flow Direction

**Fuel Cell**
- Cathode +  
- Load  
- Anode -  
- MEA

**Electrolysis**
- + Anode  
- Supply  
- + Cathode

**Advantages**
- Simple Power Electronics
  - Optimized Flow Channel designs

**Disadvantages**
- Complex Fluidic System
  - Significant safety mitigation efforts required
    (Required mitigations prevent this configuration in crewed missions)
  - Very slow mode transition times
Primary Fuel Cells vs. Primary Battery

**Electrical Power** to enable and augment exploration activities

- **Primary Metric = Specific Power (W/kg)**
- **Primary Battery**
  - 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
The Artemis Program Snapshot

- Space Launch System
- Commercial Lunar Payload Services
- The Gateway in lunar orbit
- Orion
- First woman and first person of color to the Moon
- Surface systems
The Artemis Program Snapshot

- Space Launch System
- Commercial Lunar Payload Services
- The Gateway in lunar orbit
- Fuel cell and electrolysis technologies support Sustainable Power, Life Support, and In-situ Resource Utilization (ISRU) activities in these domains
- First woman and first person of color to the Moon
- Surface systems
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
Electrochemical 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 in space
  - Cryogenic Fluid Transfer in μ-gravity
- 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
The Lunar Environment

- The average temperature on the Moon (at the equator and mid latitudes) varies from 90 Kelvin (-298 °F or -183 °C), at night, to 379 Kelvin (224 °F or 106 °C) 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 °F or -238 °C).
- 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.
Hydrogen and Fuel Cells for Lunar Exploration

- Fuel cells can provide energy storage to provide power in locations near humans where nuclear power may not be an option
- Regenerative fuel cell can provide continuous power for longer-term operations (such as the lunar night)
- Hydrogen enables energy storage and transportation in the challenging lunar environment
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.)
Reactant Generation Activities

1. Proton Exchange Membrane (PEM) Electrolysis
   - ISS Advanced Oxygen Generator Assembly (AOGA)
   - Regenerative Fuel Cell Project
   - High Pressure PLSS O₂ Tank Recharge
   - IHOP PEM Water Electrolysis/Clean-up – Paragon
   - Lunar Propellant Production Plant (LP3) – Skyre
   - Metal Oxidation Warming System Fuel Cell - Maxar

2. Solid Oxide Electrolysis (SOE)
   - Lunar Ice Processing – CSM/OxEon
   - Production of Oxygen and Fuels from In-Situ Resources on Mars – OxEon
   - Redox Tolerant Cathode for Solid Oxide Electrolysis Stacks – OxEon
   - 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

3. Alkaline (Dirty Water) Electrolysis
   - Advanced Alkaline Electrolysis (AAE) – Teledyne
   - Advanced Alkaline Reversible Cell (AARC) – pH Matter
   - Bifurcated Reversible Alkaline Cell for Energy Storage (BRACES) – pH Matter

   - Polar Resources Ice Mining Experiment-1 (PRIME-1)
   - Resource Recovery with Ionic Liquid for Exploration (RRILE)
   - Molten Regolith Electrolysis (MRE)
   - Production of Oxygen and Fuels from In-Situ Resources on Mars (O2PM) - OxEon Energy LLC
   - Integrated Architecture Trade Studies on ISRU Technologies for Human Space Exploration - University of Illinois
   - Carbothermal Reactor Risk Reduction Testing and Analytical Model Development - Sierra Nevada Corp./Orbitec
   - Redox Tolerant Cathode for Solid Oxide Electrolysis Stacks - OxEon Energy, LLC
   - Helium and Hydrogen Mixed Gas Separator - Skyhaven Systems, LLC

Funding Sources

<table>
<thead>
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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 \( \text{H}_2 \) and \( \text{O}_2 \)), 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 \( \text{O}_2 \)
- Single Stage (both ways): 40 to 50 mT \( \text{O}_2/\text{H}_2 \)

A Kilogram of Mass Delivered Here...

<table>
<thead>
<tr>
<th>Ground to LEO</th>
<th>LEO to Lunar Orbit (1-2)</th>
<th>LEO to Lunar Orbit (1-2; e.g., Orion Crew Module)</th>
<th>LEO to Lunar Surface (1-3, e.g., Descent Stage)</th>
<th>Lunar Surface to Earth Surface (3-4; e.g., Lunar Sample)</th>
<th>LEO to Lunar Surface to Lunar Orbit (1-2; e.g., Ascent Stage)</th>
<th>LEO to Lunar Surface to Earth Surface (1-2; e.g., Crew)</th>
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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 H₂ 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
Reactant Transfer and Storage

Current cryogenic activities:

1. Cryogenic Propellant Production and Storage
   • Demonstration of benefits of MLI and Vapor Cooling with hydrogen (SHIIVER)
   • Two stage cooling (90 K and 20 K) of a liquid hydrogen tank
   • Demonstration of radio frequency mass gauging in hydrogen
   • Ground demonstration of hydrogen liquefaction and storage – Blue Origin
   • Lunar Propellant Production Plant (Hydrogen and Oxygen) – Skyre

2. Cryogenic Propellant Management and Transfer
   • Space Launch System ground and flight systems
   • Transfer of densified (sub-atmospheric) hydrogen into a flight-like tank
   • Develop and test coupler prototypes for refueling spacecraft – > 8 different approaches (combination of funding sources)
   • Human Landing System development for in-space and lunar landing systems – SpaceX/Blue Origin/Dynetics
   • In-space demonstration mission using liquid hydrogen – Lockheed Martin
   • Demonstration of a smart propulsion LOX/LH2 cryogenic system on a Vulcan Centaur upper stage testing precise tank pressure control, tank-to-tank transfer, and multi-week propellant storage – ULA
Power Generation

• Fuel cells support DC electrical power bus
  o Multiple reactant types and grades (e.g. O₂/H₂ or O₂/CH₄)
  o Enable CLPS landers to use CH₄ propellant for Power

• Applications
  o Mars/Lunar Landers
    ❖ CH₄ lowers LH₂ maintenance power during transit
  o Lunar/Mars surface systems
    ❖ Uncrewed experiment platforms (0.1 kW to ~ 1 kW)
    ❖ Crewed/uncrewed rovers (~ 2 kW to ~ 10 kW)
    ❖ Crewed habitation systems (~ 10 kW modules)

Energy Storage

• High specific energy (W·hr/kg) means to store and release electrical and thermal energy
  o Lunar night: ~100 hrs (south pole) to 367 hrs (equator)
  o Waste heat helps systems survive the lunar thermal environment (-173°C to +105°C)
  o Targeting ≥ 50,000 hours maintenance interval

• Applications
  o Crewed Lunar surface systems (36 kW·hr to ≥ 1 MW·hr)
  o Lunar sensor network (≤ 5 kW·hr)
Power Production Activities

1. Proton Exchange Membrane (PEM) Fuel Cells
   - Regenerative Fuel Cell Project
   - Advanced Modular Power and Energy System (AMPES) – Infinity Fuel Cell & Hydrogen
   - Hydrogen Electrical Power System (HEPS) – Teledyne
   - Lunar Lander Fuel Cell (LLFC) – Blue Origin

2. Solid Oxide Fuel Cells (SOFC)
   - Surface Power Generation from Lunar Resources and Mission Consumables - Precision Combustion
   - 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

3. Alkaline (Dirty Water) Fuel Cells
   - Advanced Alkaline Reversible Cell (AARC) – pH Matter
   - Bifurcated Reversible Alkaline Cell for Energy Storage (BRACES) – pH Matter

3. Other Technologies
   - Lunar Regolith Hydrogen Reduction using a Hydrogen Plasma (CIF)
   - Extraterrestrial Metals Processing - Pioneer Astronautics
   - Helium and Hydrogen Mixed Gas Separator - Skyhaven Systems, LLC

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Questions
Thank you for your attention.