Update on NASA Applications using Solid Oxide Fuel Cell and Electrolysis Technologies

Ian Jakupca
NASA Glenn Research Center
21 October 2021
Presentation Overview

- NASA Exploration
- NASA Solid Oxide Fuel Cell and Electrolysis Applications
  - In Situ Resource Utilization (ISRU)
  - Sustainable Power
- Summary

Mars Oxygen ISRU Experiment (MOXIE)
Aboard Perseverance, demonstrated the first production of oxygen from the atmosphere of Mars Apr. 2021.
We’re going to the Moon to learn to live on other planets and for the benefit of all humanity.

With the Artemis lunar exploration program, NASA will put the first woman and first person of color on the lunar surface and build a sustainable presence there and in lunar orbit.
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
- Solid Oxide technologies support Sustainable Power and In-situ Resource Utilization (ISRU) activities in these domains
- Orion
- First woman and first person of color to the Moon
- Surface systems
ARTEMIS BASE CAMP
A truly sustainable infrastructure 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
EXPLORATION CAPABILITIES

The technologies and systems that allow the crew to thrive and work in space

• Regenerative life support systems enable longer-duration missions
• Crew health and performance technology keeps astronauts safe and healthy
• New systems reduce mass, volume, and the need for resupply
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

A Kilogram of Mass Delivered Here...

<table>
<thead>
<tr>
<th>Ground to LEO</th>
<th>LEO to Lunar Orbit (1→EML1)</th>
<th>LEO to Lunar Surface (1→EML2)</th>
<th>LEO to Lunar Orbit to Earth Surface (1→Earth Surface)</th>
<th>Lunar Surface to Earth Surface (EML2→Earth Surface)</th>
<th>LEO to Lunar Surface to Lunar Orbit (EML1→EML2→EML1)</th>
<th>LEO to Lunar Surface to Earth Surface (EML2→Earth Surface)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-</td>
<td>4.3 kg</td>
<td>7.5 kg</td>
<td>9.0 kg</td>
<td>14.7 kg</td>
<td>19.4 kg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20.4 kg</td>
<td>87.7 kg</td>
<td>183.6 kg</td>
<td>300 kg</td>
<td>396.8 kg</td>
</tr>
</tbody>
</table>

Geostationary Earth Orbit (GEO)
Low Earth Orbit (LEO)
Low Lunar Orbit (LLO)
Earth-Moon Lagrange Point 1 (EML1)
Support Vehicles
Personnel, Cargo, and Support Vehicles Cargo

Personnel, Cargo, and Support Vehicles Cargo
In Situ Resource Utilization (ISRU) on the Lunar Surface

ISRU Functional Block Diagrams

Functional Block Diagrams

- Help understand connectivity (interfaces/requirements):
  - Internally
  - With other Technology Plans and Disciplines
  - Cross-cutting

- Focus assessment of technology options in each sub-function
  - Used for technology and gap assessments

- Understand influence of technologies on complete system
Solid Oxide Technologies can:

- Tolerate high contamination levels
- Integrate well with high temperature ISRU processes
- Generate H₂ and O₂
- Purify / Compress O₂
- Run reversibly to provide Emergency power for limited time periods
Solid Oxide Technologies in ISRU

**Applications**
- **In-situ Resource Utilization (ISRU)**
  - Balance Design \( (H_2 \approx O_2) \) at low (≤ 50 psia) to medium pressures (≤ 250 psia)
    - Oxygen for propellants and/or Life-support applications
    - Hydrogen for propellants, chemical feed-stock, or metal processing
  - Long-term performance and reliability tolerating contaminated water sources
  - Process ISRU mined water containing inert and chemically active contaminants

**Technology Focus**
- Scale-up
- Tolerance to contaminants
  - Metal seals
    - Increased pressure capability
    - Improved thermal cycling capability
- Alternative electrolytes to improve
  - Ionic conductivity
  - Thermal cycling capability

**Active Projects**
- 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
- Carbothermal Reduction Reactor Design - Sierra Nevada Corp.
- Carbothermal Reactor Risk Reduction Testing and Analytical Model Development - Sierra Nevada Corp./Orbitec

**Funding Sources**

<table>
<thead>
<tr>
<th>Source</th>
<th>Program</th>
</tr>
</thead>
<tbody>
<tr>
<td>Internal NASA Activity</td>
<td>BAA</td>
</tr>
<tr>
<td>Tipping Point / ACO</td>
<td>SBIR / STTR</td>
</tr>
</tbody>
</table>

**Operational Pressures, MPa**

- Exact Requirements are Mission Dependent

**H₂ Production Rates, mol/hr**

- Energy Storage
- ISRU
- ECLSS

**Graphs and Diagrams**

- Operational pressures and hydrogen production rates.
Solid Oxide Technologies in Sustainable Power

**Power Generation**
- Fuel cells support DC electrical power bus
  - Multiple reactant types and grades (e.g. O₂/H₂ or O₂/CH₄)
  - Enable CLPS landers to use CH₄ propellant for Power
- Applications
  - Mars/Lunar Landers
    - CH₄ lowers LH₂ maintenance power during transit
  - 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
  - Lunar night: ~100 hrs (south pole) to 367 hrs (equator)
  - Waste heat helps systems survive the lunar thermal environment (-173°C to +105°C)
  - Targeting ≥ 50,000 hours maintenance interval
- Applications
  - Crewed Lunar surface systems (36 kW·hr to ≥ 1 MW·hr)
  - Lunar sensor network (≤ 5 kW·hr)
Solid Oxide Technology Focus for Sustainable Power

**Power Generation**
- **Scale-up**
- **Metal seals**
  - Increased pressure capability
  - Improved thermal cycling capability
- **Alternative electrolytes to improve**
  - Ionic conductivity
  - Stability
  - Thermal cycling capability

**Energy Storage**
- **Scale-up**
- **Metal seals**
  - Increased pressure capability
  - Improved thermal cycling capability
- **Alternative electrolytes to improve**
  - Bidirectional ionic conductivity
  - Bidirectional stability
  - Thermal cycling capability

**Active Projects**
- Propellant Fueled Solid Oxide Fuel Cell (PropFC) - Precision Combustion
- Robust and Reversible Metal-Supported Solid Oxide Cells for Lunar & Martian Applications – NexTech and Washington St. Univ.
- Efficient, High Power Density Hydrocarbon-Fueled Solid Oxide Stack System - Precision Combustion (1)
- Highly Efficient, Durable Regenerative Solid Oxide Stack - Precision Combustion
- Reversible Protonic Ceramic Electrochemical Cells (RePCEC) – Special Power Sources (2) and Kansas State University

**Funding Sources**
- Internal NASA Activity
- Tipping Point / ACO
- BAA
- SBIR / STTR

**Internal Hydrocarbon Reforming**

**RePCEC Solid Oxide Tube Bundle** (2)
Presentation Summary

- NASA Exploration
- NASA Solid Oxide Fuel Cell and Electrolysis Applications
  - In Situ Resource Utilization (ISRU)
  - Sustainable Power
- Summary

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