The Development of Fuel Cell Technology for NASA’s Human Spaceflight Program

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Trade Space for Electric Power Systems

Automotive Power Systems:

- Development, Production & Operation Cost ($/kW)
- Specific Power/Energy (kW/kg, kW/l, kWh/kg, kWh/l)
- Emissions (NO\textsubscript{x}, CO\textsubscript{x}, noise)

Constraint: Public Safety
Trade Space for Electric Power Systems

Spacecraft Power Systems:

- Specific Energy (kWh/kg)

- Specific Energy (kWh/kg)

- Specific Energy (kWh/kg)

- Development Cost

Constraint: Full Mission Reliability
Power Generation Specific Energy Trade Space
Energy Storage Specific Energy Trade Space

RAGONE CHART

Discharge Time, \( h = \frac{\text{Specific Energy, Wh/kg}}{\text{Specific Power, W/kg}} \)

Specific Power, W/kg

Specific Energy, Wh/kg

Fuel Cells

Cells

Pb-Acid
Spiral Wound

Ni-Cd
High Power

Li-ion
AgO-Zn

Ni-MH
High Energy

Li-Polymer

Ni-H₂

AgO-Zn

Pb-Acid
Human Space Flight Energy Storage Roadmap

Battery Solutions
- Mercury 1961
- Apollo LEM 1968
- Skylab 1973
- International Space Station 1998
- Orion MPCV 2016

Fuel Cell Solutions
- Gemini 1964
- Apollo CSM 1967
- Shuttle Orbiter 1981

Forward Requirements
- Full reactant storage
- Pure reactants
- Gravity independent
- Maximum efficiency
- Load following
- Full mission durability
- Affordable development
Elements of A Fuel Cell Power System

Fuel Processor (Reformer)
- Sulfur Removal
- Steam Reforming
- Partial Oxidation
- Water-Gas Shift
- Preferential Oxidation

Fuel Cell Stack

Inverter

H₂O (SOEC, Alkaline)

CO₂+CO

Reformate (H₂+CO₂+CO)

Fuel Processor

H₂O

O₂

H₂O (PEM)

DC Power

Heat

Electric power

Heat

IEEE Globecom, Houston, TX

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Human Space Flight Fuel Cell Roadmap

Fuel Cell Solutions
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Forward Requirements

Gemini 1964
Apollo CSM 1967
Shuttle Orbiter 1981
Human Space Flight Fuel Cell Roadmap

Gemini Fuel Cell

- Proton exchange membrane (sulfonated polystyrene)
- Catalyst: 28 mgPt/cm²
- 820 mV @ 40 mA/cm² (1.0 kW)
- 200 hr operating life
- 21 °C operating temp
- Flight set of 2
- 30 W/kg
- 0.4 kWh/kg with 1 reactant set

Fuel Cell Solutions
- Full reactant storage
- Pure reactants
- Gravity independent
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Forward Requirements

Gemini 1964
Apollo CSM 1967
Shuttle Orbiter 1981
Human Space Flight Fuel Cell Roadmap

Apollo Fuel Cell

- Mobile alkaline electrolyte
- Catalyst: Ni
- 894 mV @ 118 mA/cm² (1.5 kW)
- 400 hr operating life
- 204 °C operating temp
- Flight set of 3
- 13.5 W/kg
- 1.2 kWh/kg with 3 reactant sets

Fuel Cell Solutions
- Full reactant storage
- Pure reactants
- Gravity independent
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- Affordable development

Forward Requirements

Gemini 1964
Apollo CSM 1967
Shuttle Orbiter 1981
**Shuttle Fuel Cell**

- Captive alkaline electrolyte
- Catalyst: 28 mgPt/cm²
- 980 mV @ 114 mA/cm² (5 kW)
- 5000 hr operating life
- 90 °C operating temp
- Flight set of 3
- 39 W/kg
- 1.6 kWh/kg with 5 reactant sets
- PEMFC considered early 1990’s

**Fuel Cell Solutions**

- Full reactant storage
- Pure reactants
- Gravity independent
- Maximum efficiency
- Load following
- Full mission durability
- Affordable development

**Gemini** 1964
**Apollo** CSM 1967
**Shuttle Orbiter** 1981

**Forward Requirements**
### Chemistries of Interest for Spacecraft Application

<table>
<thead>
<tr>
<th>Chemistry</th>
<th>Alkaline Fuel Cell (AFC)</th>
<th>Proton Exchange Membrane Fuel Cell (PEMFC)</th>
<th>Solid Oxide Fuel Cell (SOFC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Capability</td>
<td>Pure H₂</td>
<td>H₂ from &quot;clean&quot; reformate</td>
<td>CO and H₂ from &quot;dirty&quot; reformate</td>
</tr>
<tr>
<td>Operating Temp.</td>
<td>~90 °C</td>
<td>~80 °C</td>
<td>~800 °C</td>
</tr>
<tr>
<td>Bootstrap Start?</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Operating Life Limiter</td>
<td>Corrosion</td>
<td>Humidity Control</td>
<td>Thermal Cycles</td>
</tr>
</tbody>
</table>

Apollo, Shuttle, Gemini, OCT, Under study for LOX/CH₄ spacecraft.
Modern Fuel Cell Technology is a Spinoff of NASA’s Human Spaceflight Program

The companies in which NASA invested created the infrastructure, engineers, and intellectual property that formed the basis of the commercial low temperature fuel cell industry that exists today.

Investment from NASA’s Human Spaceflight Program in the 1960’s – 1980’s brought fuel cells from the laboratory to their first practical application.

NASA continues to drive innovations in spacecraft low temperature fuel cell technology development while leveraging commercial advances.
PEM Fuel Cell Development

SLI/NGLT/OSP/ETDP/OCT PEMFC Technology Programs

PEMFC Forward Goals:
- 10,000 hrs Operating Life (Shuttle AFC 5,000 hrs)
- Highest Reliability
- 920 mV @ 100 mA/cm^2 (Shuttle AFC 980 mV)
- 136 W/kg (Shuttle AFC 39 W/kg)

Ballard FC Stack
Operates >11,000 hrs.

Passive Short Stack Testing

Testing of Teledyne Breadboard

Testing of Teledyne Eng. Model


“Non-Flow-Through” SBIR Efforts
Primary
Back-up
Back-up

“Balance of Plant” (BOP) Evolution

Shuttle AFC

Teledyne PEMFC Breadboard & Engineering Model

Ejector-Based “Passive” or “Flow-Through” Balance-of-Plant (BOP)

“Non-flow-through” Concept

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PEM Fuel Cell Development

Single Cell Polarization Curves (as measured)

Jet Propulsion Laboratory
Nafion 115
4.0 mg/cm² Pt unsupported cathode
~65% RH @ inlet
70 °C
300 kPa abs H₂/O₂
Narayan et al, STAIF 2007

Nafion 111
0.5 mg/cm² PtC-supported cathode
60% RH @ inlet
80 °C
100 kPa abs H₂/O₂

0.58 V
0.88 V

Current Density (mA/cm²)

E_{cell} (V)
When combined with $O_2/CH_4$ propulsion, Solid Oxide Fuel Cell technology enables a smaller, simpler spacecraft.

**Notional Lander Concepts**

- **H$_2$/O$_2**
- **CH$_4$/O$_2**

**Descent Main Propulsion**

**PEMFC Power**

**RCS Propulsion**

**Active Heat Rejection**

**Integrated Propulsion and SOFC Power**

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**ONR/NUWC – DOE/NETL UUV Concept**

- Logistics grade S-8/JP-8 fuel
- Logistics grade liquid $O_2$ oxidant
- Steam reforming
- Complete $CO_2$ capture
- Active cathode cooling via $O_2$ stream

**NASA spacecraft SOFC concept**

- Partial Oxidation reforming
- Deadheaded $O_2$ on cathode
- Cooling via passive conduction to radiator