Fuel Cell 101

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Distribution Statement A: Approved for public release; distribution is unlimited.
Fuel Cell Operation

• A Fuel Cell is an electrochemical power source

• It supplies electricity by combining hydrogen and oxygen electrochemically without combustion.

• It is configured like a battery with anode and cathode.

• Unlike a battery, it does not run down or require recharging and will produce electricity, heat and water as long as fuel is supplied.

\[ H_2 \rightarrow 2H^+ + 2e^- \quad \text{and} \quad O_2 + 2H^+ + 2e^- \rightarrow 2H_2O \]
Fuel Cell System

Fuel Processing

Heat & Water

Useful Heat

Hydrogen Rich Gas

Power Section

Power

Clean Exhaust

Power Conversion/Conditioning

Power to Application

Controls

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Fuel Cell System
# Fuel Cell Types

<table>
<thead>
<tr>
<th>Fuel Cell Type</th>
<th>Electrolyte</th>
<th>Cell Temp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton Exchange Membrane (PEM)</td>
<td>Polymer Membrane (Solid)</td>
<td>70-90°C</td>
</tr>
<tr>
<td>Phosphoric Acid (PAFC)</td>
<td>Phosphoric Acid (Liquid)</td>
<td>120-180°C</td>
</tr>
<tr>
<td>High Temp PEM (HTPEM)</td>
<td>Phosphoric Acid Polymer (Solid)</td>
<td>120-180°C</td>
</tr>
<tr>
<td>Molten Carbonate (MCFC)</td>
<td>Potassium Lithium Carbonate (Liquid)</td>
<td>650°C</td>
</tr>
<tr>
<td>Solid Oxide (SOFC) (Tubular, planar)</td>
<td>Solid Zirconium Oxide Ceramic (Solid)</td>
<td>700-950°C</td>
</tr>
</tbody>
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# Fuel Cell Types

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<td><strong>Phosphoric Acid (PAFC)</strong></td>
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Polarization Curve
Polarization or Operational Voltage, V, Curve

Theoretical EMF or Ideal Voltage

Cell Voltage

INCREASE EFFICIENCY

Current Density (mA/cm^2)

INCREASE POWER DENSITY

TARGET OPERATION

Region of Activation Polarization (reaction rate loss)

Region of Concentration Polarization (mass transport limited)

Region of Ohmic Polarization (resistance loss)
Fuel Cell System

HEAT & WATER
CLEAN EXHAUST
USEFUL HEAT
POWER CONVERSION / CONDITIONING
POWER TO APPLICATION

POWER SECTION

FUEL PROCESSING
FUEL
HYDROGEN RICH GAS
AIR/OXYGEN

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Fuel Reforming

- Fuel Reforming refers to processes that change the fuel from a liquid hydrocarbon to a gas-phase, fuel-rich, stream
  - Fuel Reforming is an endothermic process
  - Heat is required to sustain the reaction

- Several processes exist; most practical ones are:
  - Partial Oxidation Reforming (with air)
  - Steam Reforming (with steam)
  - Autothermal Reforming (with air and steam)

- Water Gas Shift is an equilibrium reaction, used to convert Carbon Monoxide and Steam into Carbon Dioxide and additional Hydrogen
Partial Oxidation Reforming

- Air reacts with fuel to form Carbon Monoxide and Hydrogen.
- Heat is supplied by oxidizing a portion of the fuel inside the reformer.

- **Pros:** Simple adiabatic reformer, high power density, high contaminant tolerance, no steam required
- **Cons:** Low efficiency, susceptible to soot formation, low pressure operation, nitrogen dilution of the product fuel

C\textsubscript{8}H\textsubscript{18} + 4 (O\textsubscript{2} + 3.8 N\textsubscript{2}) → 8 CO + 9 H\textsubscript{2} + 3.8*4 N\textsubscript{2}

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Steam Reforming

- Steam reacts with fuel to form Carbon Monoxide and Hydrogen.
- Heat is supplied by burning fuel external to the reformer, through heat exchange

**Pros:** High efficiency, capable of high pressure, air compression not required, fuel not diluted by nitrogen

**Cons:** Higher complexity, low power density, scalability, low contaminant tolerance, high steam flow, high temperature heat exchange

\[ C_8H_{18} + 8H_2O \rightarrow 8CO + 17H_2 \]
Autothermal Reforming

- Combines partial oxidation with steam reforming. Air and Steam react with fuel to form Carbon Monoxide and Hydrogen.
- Heat is supplied by oxidizing a portion of the fuel inside the reformer.

- **Pros:** Adiabatic operation, greater efficiency than POX, high power density, contaminant tolerance
- **Cons:** Higher complexity control, requires steam and air, nitrogen dilutes the fuel stream

\[ C_8H_{18} + 3.6 \ (O_2 + 3.8 \ N_2) + 0.8 \ H_2O \rightarrow 8 \ CO + 9 \ H_2 + 13.7 \ N_2 \]
Water Gas Shift Reaction

- Steam reacts with Carbon Dioxide to form Carbon Monoxide and increased Hydrogen. The reaction is slightly exothermic.
- Hydrogen yield is limited by temperature kinetics and equilibrium

- **Pros:** Simple adiabatic reactor, increases hydrogen yield from all types of reformers, hydrogen yield better at lower temperatures.
- **Cons:** Low power density, requires additional steam, low contaminant tolerance, poor kinetics at low temperature

\[ \text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + \text{H}_2 \]
Membrane Separation

- Palladium-alloy membranes can be used to separate pure Hydrogen from a Hydrogen-rich reformate stream
- Mechanism involves diffusion of hydrogen atoms through the solid membrane metal. Produces high-purity hydrogen
- Hydrogen yield is limited by the difference in hydrogen gas partial pressure across the membrane

- **Pros**: Simple reactor, no moving parts, makes ultra high purity hydrogen, low power requirements
- **Cons**: Expensive materials, high pressure reformers increase yield
Commercial

Electronics

Residential, APU

Automotive

Industrial, Dist. Gen

Locomotive

Power (kWe)

.01 .1 1 10 100 1,000 10,000

DMFC SOFC PEM/HT PEMFC PAFC MCFC

Multiple Modules

Soldier Power

Portable Power

UV/Small Craft/Submersible

Vehicles, Small MEP

Ship Service, Large MEP

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Fuel Cell Benefits

**Reduced Acquisition & Life Cycle Costs**
- Greater System Efficiencies
- Reduced Maintenance Costs
- Enables Spiral Development

**Enhanced Survivability**
- Reduced IR Signature
- Reduced Acoustic Signature
- Distributed Power Generation

**Design Flexibility**
- Modular Approach to Ship Power
- Multi Platform Applicable

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Even at Its Infancy, Fuel Cell System Efficiency Starts Where the Other Technologies End
Airborne noise: Sound intensity level (dB) in engine room corrected to 10 feet distance

Airborne Noise

Diesels

Gas Turbines

1st Generation SSFC Module (w minimal isolation)
• Fuel Cells have higher efficiency, with correspondingly lower CO2 emissions.

• Fuel cells are not a combustion process, so they have greatly reduced NOx, CO, hydrocarbon, and particulate emissions.

• Low SO2 output is a function of higher efficiency and low/no sulfur in fuel
Power Generation Technologies

Volumetric Density Comparison

Fuel Cell System Volumetric Density Dependent on Overall System Design