How Does a Hydrogen Fuel Cell Work?

Anode

\[ H_2 \rightarrow 2H^+ + 2e^- \]

Cathode

\[ 2H^+ + 2e^- + \frac{1}{2}O_2 \rightarrow H_2O \]

**Anode Reaction:** \( 2H_2 \rightarrow 4H^+ + 4e^- \)

**Cathode Reaction:** \( O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \)

**Overall Cell Reaction:** \( 2H_2 + O_2 \rightarrow 2H_2O \)
Stack “Repeat Parts”

- Cooler
- Cathode end plate
- Cushion
- MEA
- Bipolar Plate
- Anode end plate
- Cushion
- Current Collector
- Isolator
- Pressure plate

Proprietary and Confidential
Fuel Cell Stack

- Air In
- Coolant In
- Coolant Out
- Air Out
- Fuel In
- Fuel Out
- Coolant Out
- Fuel Out
Fuel Cell Stack Performance

- CSA# 80044
- TE 901 = 150°C
- Oil Coolant Flow Rate = 3.0 LPM = 0.75

Cathode Utilization: 50%
Anode Utilization: 66.7%

Current Density (mA/cm²)

Design Point

Avg. Cell Voltage (V)

Power Density (mW/cm²)

H2(Dry)/Air (Dry)
SimRef(Dry)/Air (Dry)
Power Density SimRef
Fuel Processing Technology

NG or Propane

Hydrodesulfurization

Steam Reforming

Water Gas Shift

Typical Composition of Natural Gas

<table>
<thead>
<tr>
<th>Component</th>
<th>Typical Analysis (mole %)</th>
<th>Range (mole %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methane</td>
<td>95.2</td>
<td>87.0 - 96.0</td>
</tr>
<tr>
<td>Ethane</td>
<td>2.5</td>
<td>1.5 - 5.1</td>
</tr>
<tr>
<td>Propane</td>
<td>0.2</td>
<td>0.1 - 1.5</td>
</tr>
<tr>
<td>iso - Butane</td>
<td>0.03</td>
<td>0.01 - 0.3</td>
</tr>
<tr>
<td>normal - Butane</td>
<td>0.03</td>
<td>0.01 - 0.3</td>
</tr>
<tr>
<td>iso - Pentane</td>
<td>0.01</td>
<td>trace - 0.14</td>
</tr>
<tr>
<td>normal - Pentane</td>
<td>0.01</td>
<td>trace - 0.04</td>
</tr>
<tr>
<td>Hexanes plus</td>
<td>0.01</td>
<td>trace - 0.06</td>
</tr>
</tbody>
</table>

R-SH + H₂ ⇌ R-H + H₂S
ZnO + H₂S ⇌ ZnS + H₂O

CH₄ + H₂O → CO + 3H₂
CO + H₂O → CO₂ + H₂
CH₄ + 2H₂O → CO₂ + 4H₂

CO + H₂O → CO₂ + H₂
Fuel Processor

Requirements:
- >115% efficiency (Suitable for 40% Elect. Efficiency)
- Pipeline NG or Commercial grade LPG
- Emissions (system):
  - NOx: <3 ppm (demonstrated in Phase II)
  - CO: <10ppm (demonstrated in Phase II)
  - SOx: Negligible (demonstrated in Phase II)
- Life: 40k + hours

Overall Reaction:
\[ \text{CH}_4 + 2\text{H}_2\text{O} \Rightarrow 4\text{H}_2 + \text{CO}_2 \]
Process Control

CE5 Controller Hardware

CE5’s ‘secret sauce’ – Process controller development using Simulink/Stateflow
Fuel Cell “System”

\[
\eta = \frac{\text{Power} + \text{Heat}}{\text{LHV of NG}} = \frac{5kW + 5.10kW}{12.5kW} = 80.8\% 
\]
ClearEdge5 Requirements

- 5 kW electrical power @ 120/240 VAC 60 Hz, with 12 kW for 7 sec (transient overload capability)
- Electrical efficiency of 40% at rated power (LHV, new system), with lifetime overall energy utilization efficiency of ≥80% in CHP mode
- Designed for base-load operation, capable of grid connect/ grid independent mode
- Provides backup power during grid outage
- Operates on residential grade natural gas or Propane
- Heat output: Up to 6.5 kW @ 65º C, suitable for hot water system, radiant heating or pool/spa heating
### Design Milestones

#### CE5 Efficiency Breakdown

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>BOL</th>
<th>After 40k Hrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrical</td>
<td>40.1%</td>
<td>35.5%</td>
</tr>
<tr>
<td>Heat</td>
<td>45.0%</td>
<td>49.8%</td>
</tr>
<tr>
<td>Total</td>
<td>85.1%</td>
<td>85.3%</td>
</tr>
</tbody>
</table>

- **Achieved**
  - System efficiency exceeds all expectations!!
  - > 20 units are currently operated in the field.
  - Over thousands of operation hours are collected.

#### CE5 Efficiency Breakdown

- **Electrical**: 40% → 35.5%
- **Heat**: 45% → 49.8%
- **Total**: 85.1% → 85.3%

#### System Features

- **Baseline design**
- **Operate at lower current density**
- **Lower system pressure drop**
- **Thermal integration with FPS**
- **Optimized design**
Remote Monitoring

Each system contains 1 GB of NVM rolling memory, equivalent to a “Black Box”

Real time monitoring of all safety and control parameters via remote HMI

Central Data Server

Real Time Data

Sends SMS or email to FSE in the event of an issue

Real time customer interface

Web monitoring system (custom integration with other home monitoring systems possible)

iPhone

[Diagram showing data flow and integration with remote monitoring system]

[Images of monitoring equipment and smartphone interface]

[Logo: ClearEdge Power, Delivering Smart Energy Today]
Why Fuel Cells? – Need More Power

**World Net Electric Power Generation**
**1990-2030**

<table>
<thead>
<tr>
<th>Year</th>
<th>Trillion kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>11.3</td>
</tr>
<tr>
<td>1995</td>
<td>12.6</td>
</tr>
<tr>
<td>2000</td>
<td>14.6</td>
</tr>
<tr>
<td>2005</td>
<td>17.3</td>
</tr>
<tr>
<td>2010</td>
<td>21.0</td>
</tr>
<tr>
<td>2015</td>
<td>24.4</td>
</tr>
<tr>
<td>2020</td>
<td>27.5</td>
</tr>
<tr>
<td>2025</td>
<td>30.4</td>
</tr>
<tr>
<td>2030</td>
<td>33.3</td>
</tr>
</tbody>
</table>

**2009 U.S. Electricity Generation by Source**

- **Coal**: 44.9%
- **Natural Gas**: 23.4%
- **Nuclear**: 20.3%
- **Hydroelectric**: 16.9%
- **Other Renewables**: 3.6%
- **Petroleum**: 1.0%

**Sources:**

**Increasing power demand driven by:**

- Fundamental shift from mechanical to electrical products
- Increasing population urbanization
Why Fuel Cells? – Environmental Impact

How You Receive Energy Today

- Natural Gas, Nuclear, Coal
  - Efficiency: 35%
  - 4223 therms

- Natural Gas
  - Efficiency: 80%
  - 2175 therms

...And Will Tomorrow

Electrochemical Conversion

- Efficiency: up to 90%
- Natural Gas

ClearEdge5 System Provides
- a 40% Reduction in Fuel Consumption
- a 37% Reduction in CO₂

Environmental Impact
- 8.35 lbs CO₂ per hour
- 34 Tons per Annum

Environmental Impact
- 5.3 lbs CO₂ per hour
- 22 Tons per Annum
## Fuel Cell microCHP vs. Solar Comparison

### High Efficiency

<table>
<thead>
<tr>
<th></th>
<th>5 kW Fuel Cell</th>
<th>5kW Solar</th>
<th>27kW Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electric Production-Annual</td>
<td>43,800 kWh</td>
<td>8000 kWh</td>
<td>43,200 kWh</td>
</tr>
<tr>
<td>Heat Production</td>
<td>51,000 kWh</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Space Required</td>
<td>6 sq. ft.</td>
<td>500 sq. ft.</td>
<td>3000 sq. ft.</td>
</tr>
</tbody>
</table>
Why Fuel Cells? – Because It Is the Right Answer!!

- **Lower Cost Power than Grid** – as low as $.06 per kWh operating cost with full heat load being utilized.

- **Cleaner than Grid Power** – 37% less CO₂ with untraceable NOₓ or SOₓ.

- **High Efficiency & Less Fuel Required** – Over 90% CHP energy efficiency requiring 40% lower fuel consumption than conventional combined cycle or heating systems.

- **Continuous Power** – Operates in both grid parallel and grid independent modes to provide uninterrupted power during grid outages.

- **Multi-Fuel & Scalable** – Operates on common infrastructure fuels available.

- **Aesthetic Design** – Compact and quiet system operates both indoors or outdoors without compromising architectural design.
Target Vertical Markets

**Commercial**
- Hotels
- Restaurants
- Health & Athletics
- Entertainment
- Agriculture & Greenhouses

**Institutional**
- Utilities
- Schools
- Government
- Medical
- Military

**Residential**
- Residential Single Family
- Multi-Tenant:
  - Planned Communities
  - Senior / Affordable Housing
  - Condos & Apartments