Who are we?
Cummins Power Generation (AKA Onan)

World Headquarters, Central Engineering, and Manufacturing for the Americas in Fridley Minnesota

1,000,000 ft²  1500 employees
Cummins Power Generation Products and Markets

**Stationary Power Markets**
- Residential
- Telecommunications
- Standby / Interruptible
- Distributed Generation

**Mobile Power Markets**
- Portables
- Marine
- Recreational Vehicle
- Commercial Mobile
- Rental

**Technologies**
- Engine Gensets
- Variable Speed and Hybrid Gensets
- Controls, Switch Gear
- Fuel Cell Program
Fuel Cells

- Who?
- What?
- Why?
- Where?
- When?
- How? (How Much?)
How is a Fuel Cell Different From a Battery?

Both cause an electrical potential through oxidation of materials

**Batteries**

Internal materials transform during charging and discharging (power and energy limited by the cell size)

**Fuel Cells**

Internal materials act as catalysts and only the fuel oxidizes (power limited by cell size, energy by the fuel tank size)
Basic elements of a battery or fuel cell

- **Anode**: Fuel or reducing electrode
- **Electrolyte**: Ion conductor
- **Cathode**: Oxidizing electrode

- **Electron flow**
- **FC Ion flow**

+ Positive

- Negative
<table>
<thead>
<tr>
<th>Fuel Cell Type</th>
<th>Electrolyte</th>
<th>Operating Temperature</th>
<th>Fuel</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEM</td>
<td>Solid Polymer Membrane</td>
<td>60-100°C 140-212°F</td>
<td>Hydrogen</td>
<td>• Quick Start&lt;br&gt;• Low Temperature Operation</td>
<td>• Expensive Catalyst&lt;br&gt;• CO Intolerance</td>
</tr>
<tr>
<td>SOFC</td>
<td>Solid Zirconium Oxide</td>
<td>700-900°C 1292-1652°F</td>
<td>Hydrogen&lt;br&gt;• Carbon Monoxide&lt;br&gt;• Methane</td>
<td>• Fuel Flexible&lt;br&gt;• Cheap Catalysts&lt;br&gt;• High Efficiency&lt;br&gt;• Solid Electrolyte</td>
<td>• High Temperature&lt;br&gt;• Startup time</td>
</tr>
<tr>
<td>AFC</td>
<td>Aqueous Potassium Hydroxide</td>
<td>90-100°C 194-212°F</td>
<td>Hydrogen</td>
<td>• Power Density</td>
<td>• Anode/Cathode Poisoned by CO₂</td>
</tr>
<tr>
<td>MCFC</td>
<td>Liquid Lithium-Potassium Carbonates</td>
<td>600-1000°C 1112-1832°F</td>
<td>Hydrogen&lt;br&gt;• Carbon Monoxide&lt;br&gt;• Methane</td>
<td>• Fuel Flexible&lt;br&gt;• Cheap Catalysts&lt;br&gt;• High Efficiency</td>
<td>• High Temp.&lt;br&gt;• Startup time&lt;br&gt;• Corrosion&lt;br&gt;• Liquid Electrolyte</td>
</tr>
<tr>
<td>PAFC</td>
<td>Liquid Phosphoric acid</td>
<td>175-200°C 347-392°F</td>
<td>Hydrogen</td>
<td>• Lower Temperature</td>
<td>• Expensive Catalyst&lt;br&gt;• Large/Heavy&lt;br&gt;• Lower Efficiency</td>
</tr>
</tbody>
</table>
Proton Exchange Membrane’s The Hydrogen Economy Fuel Cell

- **Proton Exchange Fuel Cell**
  - *Protons (Hydrogen Nuclei) Cross Electrolyte*
  - Solid Electrolyte
  - Requires ultra-pure Hydrogen.
  - Chemical to Electrical conversion efficiencies
    - ~50%
  - System efficiencies
    - 35% - 45%
Solid Oxide Fuel Cells
The Omnivorous Fuel Cell

Solid Oxide Fuel Cell (SOFC)

- **Oxygen Ions Cross the Electrolyte**
- Operating Temperature <600-800 °C
- Well suited to run on gasified coal or Bio-Fuels
- System Efficiencies ~40-60%
SOFC Stacks

SOFC Planar Construction
- Solid electrolyte, supported by Anode material.
- Cell interconnects made of stainless steel.

SOFC Cells

- **Anode** – nickel-zirconia cermet, ~ 1 mm thick
- **Electrolyte** – yttria-stabilized zirconia (YSZ), ~ 5 µm thick
- **Cathode** – conducting ceramic, ~ 50 µm thick

All Courtesy of Versa Power
Why Solid Oxide Fuel Cells (SOFC’s)?

- Simplified fuel reformation for HC fuels (CO is fuel constituent, trending towards direct internal reforming of Methane)
- No water management in stacks
- Potential for low cost / no precious metals
- No external cooling required
- High quality waste heat stream
- High efficiency

Challenges
- Thermal management (start up, shut down, transients) – startup time
- Degradation
- Cost
Fuel Cells are not an energy source.

- They are an energy conversion device.
  - Chemical Potential Energy to Electrical Energy.

- For automotive use there is another step;
  - Chemical Potential to Electrical Energy to Mechanical Energy.
Fuel cells and the Hydrogen economy can be mutually exclusive!

Not all fuel cells need a Hydrogen economy.

– Solid Oxide Fuel Cells (SOFC’s) can use Carbon Monoxide and/or Hydrogen for fuel.
  • SOFC’s have been demonstrated running on gasified coal, natural gas, even peanut shells.
– Proton Exchange Membrane Fuel Cells (PEM’s) do require Pure Hydrogen.

The fuel, and conversion, debate will continue to rage, will the final arbiter be the free market?

Misconception; Fuel Cells are a Renewable Energy Source

- Conventional heat engine’s are also energy conversion devices.

- Electrical power generation from a heat engine, has another step;
  - Chemical Potential to Heat Energy to Mechanical Motion to Electrical Energy.

- The common denominator, Chemical Fuel.
Fuel cells and the Hydrogen economy can be mutually exclusive!

The Hydrogen economy does not need fuel cells.

- Hydrogen can be burned in internal combustion engines.
  - Ford Model U has near zero emissions and achieves 38% efficiency on Hydrogen.
  - BMW has developed a dual fuel gasoline/Hydrogen spark ignition engine.
  - "The thermal efficiency of a hydrogen internal combustion engine will be more than 50 percent." – Raymond Freymann, managing director of BMW Group Research and Technology
Misconception;
2x to 3x Improvement In Efficiency 
Versus a Heat Engine

Theoretical Maximum Fuel Cell Efficiency (H₂ Fuel @STP)

\[ \eta_{\text{ideal}} = \frac{\Delta G}{\Delta H} = \frac{237.1}{285.8} = 0.83 = 83\% \]

*Fuel Cell Handbook Version 7

• Fuel Cell
  – Irreversibility's
    • Activation losses
      – These are larger for PEM’s than for SOFC’s
    • Electrical conduction losses
    • Gas transport losses
    • Fuel utilization losses
    • Pumping and system losses
  – Efficiencies peak at mid load conditions
Misconception;
2x to 3x Improvement In Efficiency
Versus a Heat Engine

Theoretical Maximum Heat Engine Efficiency (H₂ Fuel in Air)
Based on Carnot Efficiency with “Real Combustion”
\[ \eta_{\text{Carnot}} = 1 - \frac{T_L}{T_H} \]
\[ \eta_{\text{ideal}} = 73\% \]
*Hassanzadeh et. al. 2005

Difference is due to irreversibility of combustion.

- **Heat Engines**
  - Irreversibility’s
    - Combustion Losses
    - Carnot Cycle limitations
    - Frictional and windage losses
    - Pumping losses
    - Heat transfer losses
  - Efficiencies peak at higher load conditions and are proportional to size
Very wide variety of fuel types and grades
Power generation fuel flexibility will be important
How Can Fuel Cells be Complimentary to a Renewable Energy Strategy?

• Simple Answer: Reversibility

![Diagram of SOFC and SOEC](http://images.energieportal24.de/dateien/downloads/brightorbleak.pdf)
Advantages of **fuel cells**

– Can have greater conversion efficiency.
  
  • Particularly for the conversion to electrical energy.
    
    – SOFC can provide 50% open cycle and potentially 70% with bottoming cycle vs. 40% for heat engines open cycle.
  
  • One of the leading arguments for fuel cells. Makes more costly renewable energy, affordable.
Higher efficiency plus high fuel costs favor evolving technology, fuel cells
High Eq. costs drive total ownership costs, particularly in less than base load applications.
Advantages of **fuel cells**

- Can have near zero harmful emissions on carbon based fuels (SOFC’s).
  - Heat engines running on Hydrogen also have near zero emissions.
  - No NOx, if you are careful.
- Fuel Cells are quiet with no vibration.
- Fuel Cells can have a reduced IR signature.
All technologies are evolving into a tight band
Ultra low FC emissions may drive BACT regulations that favor fuel cells in non containment areas
Disadvantages of fuel cells

– Presently more costly.
  • Not a mature technology.
  • PEM’s require platinum for Catalysts.

– Start up issues.
  • SOFC’s will always take tens of minutes to start.
  • Starting a PEM at -40°F is difficult.
The System

- Fuel Cell Stacks center piece of a larger system.
  - Fuel Cells by themselves are clean, balance of plant may not be.
  - Balance of Plant (BOP)
    - Thermal, fluid management
      - Control flows to match current demand, and fuel utilization requirements.
      - Control stack average temperature.
      - Control stack temperature gradients.
    - Combustor cleans up exhaust
      - MUST BE CAREFUL WITH DESIGN OF COMBUSTOR.
  - Fuel processor
    - Other than Natural Gas, SOFC needs some fuel processing
    - Greatly simplified versus a PEM, however.
Mobile SOFC Balance of Plant

- Air
- Fuel
- Preheat Air Fuel
- Combustor
- Exhaust
- Recuperator
- Trim HX
- Fuel Cell Stacks (Hot Box)
- CPOX
- Mixer-Heater
- Load
Stationary SOFC BOP

Fuel Cell System
Power Electronics

- Load management
  - Fuel Must Lead ON Load, and Must Lag OFF Load
- Supply a buffer between required load power and fuel cell dynamics (Fuel processor limits transient performance).
  - Control stack loading to a safe rate.
  - Maintain supplemental energy storage.
    - Battery based hybrid system
  - Generate stable AC power to user.
Fuel Cell Power Electronics

Fuel Cell

Fuel Cell DC Bus (70-112Vdc)

Fuel Cell Voltage Boost 6.0kW

Control Signals, for Boost Enable and Current Limit.

Fuel Cell Control

Load Control Handshake Signals

High Voltage DC Bus (200-220Vdc)

DC/AC Inverter

Battery Boost/Charger 3kW

12V Lead Acid Battery. Voltage Range 10.5-13.8Vdc

12V Battery Bank

120Vac 60Hz 10kW Output

Onan Hybrid QD Electronics

Raptor Power Electronics

Control Signals, for Boost Enable and Current Limit.
Affordable Hybrid Fuel Cell System

- Ceramic solid-oxide technology
  - Clean, efficient, silent power
  - 10 kW power system
  - Improved emissions
  - Improved efficiency
  - Maintenance benefits over engine gensets
  - Longer life
  - Lower costs over longer term

- Key Markets
  - RV
  - Commercial mobile
  - Telecommunications standby
  - Distributed Generation
  - Residential

Fuel Cell Module
Packaged System
Fuel Cell System Mock-Up

- Operator controls
- Power Module
- Fuel cell boost
- BOP Section

Dimensions:
- 915mm (36”)
- 635mm (25”)
- 635mm (25”)

Image of fuel cell system mock-up with Cummins Power Generation branding.
Fuel Cell System Components

Display Panel

Inverter / Charger

Power Unit

Transfer Switch
Siemens 250kW SOFC

- Siemens Tubular SOFC
  - 250kW Demo Unit
  - Fuel Cell Electrical Efficiency 48% *(Without Turbine Bottoming Cycle)*
  - Life Expectancy 50-100k Hours *(Presently @ 20k hours)*
  - Virtually Zero Emissions, No So$_x$, CO, <0.5ppm NO$_x$
SECA is a vital part of the DOE’s ultimate goal, called Vision 21

- Clean, efficient electric power generation with ~60% Efficiency on coal ~70% on natural gas 2015.
- Think about it, ~60% efficient electric power production on Coal or Renewable Bio-Fuels!
- Can also include Hydrogen separation.