



Fuel Cells

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PDH: 3

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Module 1: Fuel Cell Fundamentals and Historical Context

Learning Objectives

By the end of this section, you will be able to:

- **Identify** the core electrochemical principles that distinguish fuel cells from internal combustion engines.
- **Evaluate** the historical progression of fuel cell technology from initial discovery to modern transportation applications.
- **Calculate** the operating voltage of a fuel cell stack based on individual cell performance.

Executive Summary: Fuel cells represent a strategic shift from thermal-mechanical energy conversion to direct electrochemical conversion, offering two to three times the efficiency of internal combustion engines while potentially eliminating tailpipe emissions.

A Brief History of Innovation

While often viewed as modern technology, the principle of the fuel cell was discovered in **1839 by William Grove, a British jurist and amateur physicist. Grove demonstrated that hydrogen and oxygen could be utilized to produce electric power, which he then used to split water into its components.**

Key Historical Milestones

- 1839: Discovery of the fuel cell principle by William Grove.
- 1960s: NASA successfully demonstrated fuel cell applications for providing power during space flight.
- 1984: The U.S. Department of Energy (DOE) began supporting intensive fuel cell R&D.
- 1998: Chicago became the first city to implement pollution-free, hydrogen fuel cell buses in a public transit system.
- 1999: Virginia Tech entered the FutureCar Challenge with a student-developed fuel cell vehicle.

Energy Conversion: Carnot Cycle vs. Fuel Cells

Licensed engineers must distinguish between the thermal limits of traditional engines and the electrochemical advantages of fuel cells.

Internal Combustion Engines (ICE)

Internal combustion engines are **heat engines** limited by the **Carnot Cycle**. They change the chemical energy of fuel into thermal energy to generate mechanical work.

Equation 1-1: Maximum Carnot Efficiency

$$\eta_{max} = \frac{T_1 - T_2}{T_1}$$

where,

- T_1 = Source temperature (degrees Kelvin)
- T_2 = Sink temperature (degrees Kelvin)

Fuel Cell Advantages

Because fuel cells convert chemical energy **directly to electrical energy**, they do not involve the conversion of heat to mechanical energy.


- Efficiency: Fuel cell efficiencies can exceed the Carnot limit even at low operating temperatures (e.g., 80°C).
- Mechanics: They require minimal maintenance due to a lack of moving parts in the power-generating stacks.

The Very Basics of Operation

A fuel cell is an electrochemical energy conversion device that produces electricity, water, and heat using fuel and oxygen from the air.

Core Operational Steps

1. Anode Side (-): Hydrogen flows in; a platinum catalyst facilitates the separation of gas into electrons and protons.
2. Membrane: Hydrogen ions (protons) pass through the center membrane, while electrons are blocked.
3. External Circuit: Electrons flow through an external circuit (powering a motor or load) to reach the cathode.
4. Cathode Side (+): Protons, electrons, and oxygen combine with the help of a catalyst to produce water.

 **Calculation Note:** The voltage from a single cell is approximately 0.7 volts. To achieve automotive-grade power, cells are stacked in series.

Equation 1-2: Stack Voltage

Operating Voltage = 0.7 volts * Number of cells

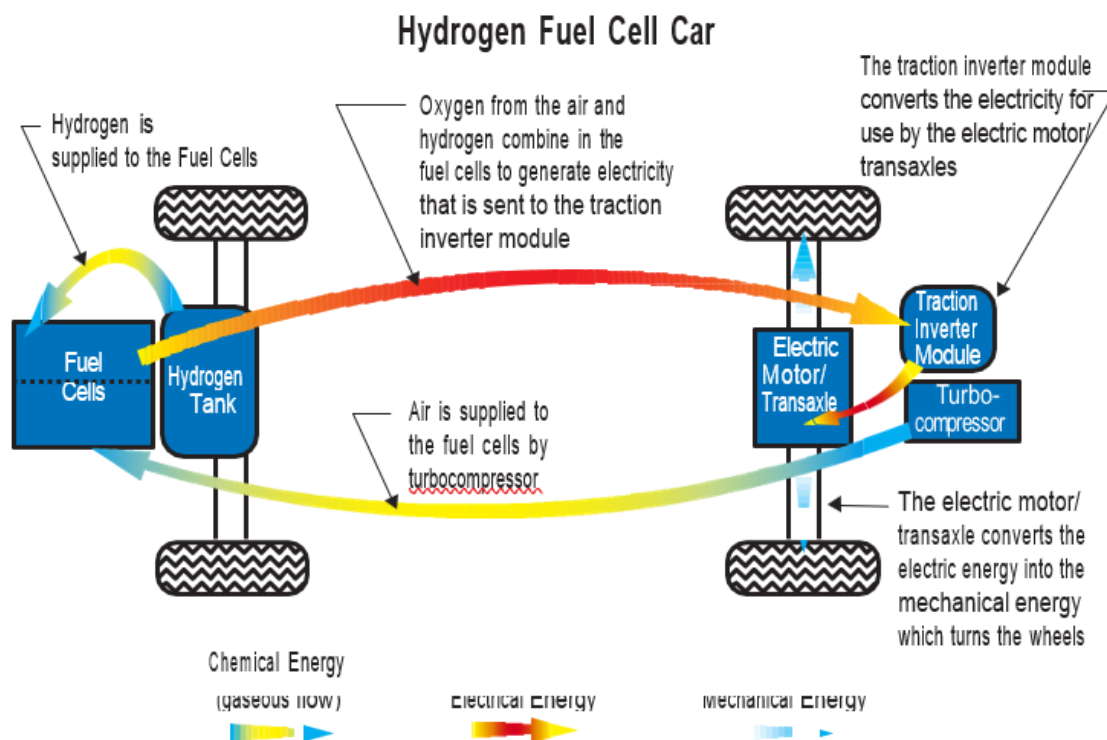
Where:

- **0.7 volts** = Typical voltage of a single cell

Comparison: Engines, Batteries, and Fuel Cells

Feature	Internal Combustion Engine	Battery	Fuel Cell
Energy Conversion	Chemical to Thermal to Mechanical	Chemical to Electrical	Chemical to Electrical
Reactant Storage	External Tank	Internal	External Tank
Refueling	Quick (Liquid Fuel)	Requires Recharging	Quick Refueling
Moving Parts	Many (High Maintenance)	None (Low Maintenance)	None (Low Maintenance)

⚠ Safety Constraint: While direct hydrogen fuel cells have **zero tailpipe emissions**, hydrogen fuel must be handled with proper engineering controls to manage its storage and distribution.



The P2000, from Ford Motor Company, is a zero-emission vehicle that utilizes a direct hydrogen polymer electrolyte fuel cell.

Checkpoint Quiz

1. Why can fuel cell efficiencies exceed the theoretical Carnot limit of internal combustion engines?

- a) They operate at significantly higher temperatures.
- b) They convert chemical energy directly to electrical energy without a thermal-mechanical step.
- c) They utilize platinum catalysts which ignore thermodynamic laws.
- d) They store reactants internally like a high-density battery.

Answer: (b). Fuel cells bypass the heat-to-mechanical energy conversion, which is the stage limited by the Carnot Cycle.

2. A design requires a fuel cell stack to provide a terminal voltage of approximately 280V. Based on the standard single-cell output of 0.7V, how many cells must be stacked in series?

- a) 200 cells
- b) 350 cells
- c) 400 cells
- d) 196 cells

Answer: (c). Using Equation 1-2 ($280V / 0.7V = 400$), 400 cells are required.

3. In a PEM fuel cell, which component is responsible for facilitating the separation of hydrogen gas into electrons and protons?

- a) The polymer electrolyte membrane
- b) The carbon backing layer
- c) The platinum catalyst at the anode
- d) The turbocompressor

Answer: (c). As hydrogen flows into the anode, the platinum catalyst facilitates the separation of the gas into electrons and protons.

Module 2: The Polymer Electrolyte Membrane (PEM) Fuel Cell

Learning Objectives

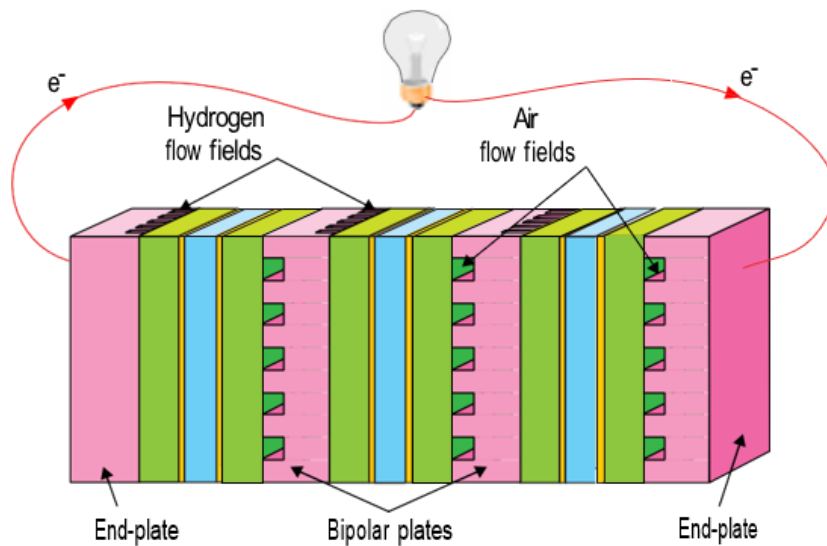
By the end of this section, you will be able to:

- **Identify** the structural and chemical characteristics of polymer electrolyte membranes used in transportation applications.
- **Evaluate** the oxidation and reduction half-reactions and the role of platinum catalysts in current generation.
- **Calculate** the total stack voltage and efficiency based on single-cell performance parameters.

Executive Summary: The PEM fuel cell is the technological cornerstone for modern zero-emission transportation, utilizing a solid polymer membrane to conduct protons while forcing electrons through an external circuit to provide regulated electrical power.

The Polymer Electrolyte Membrane (Electrolyte)

The electrolyte defines the fuel cell type. In a PEM system, the electrolyte is a solid, organic polymer—specifically poly[perfluorosulfonic] acid. The most prevalent material, Nafion™, resembles household plastic wrap but is more substantial, with thicknesses ranging from 50 to 175 microns (comparable to 2 to 7 pieces of paper).



A 3-cell fuel cell stack with two bipolar plates and two end plates.



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