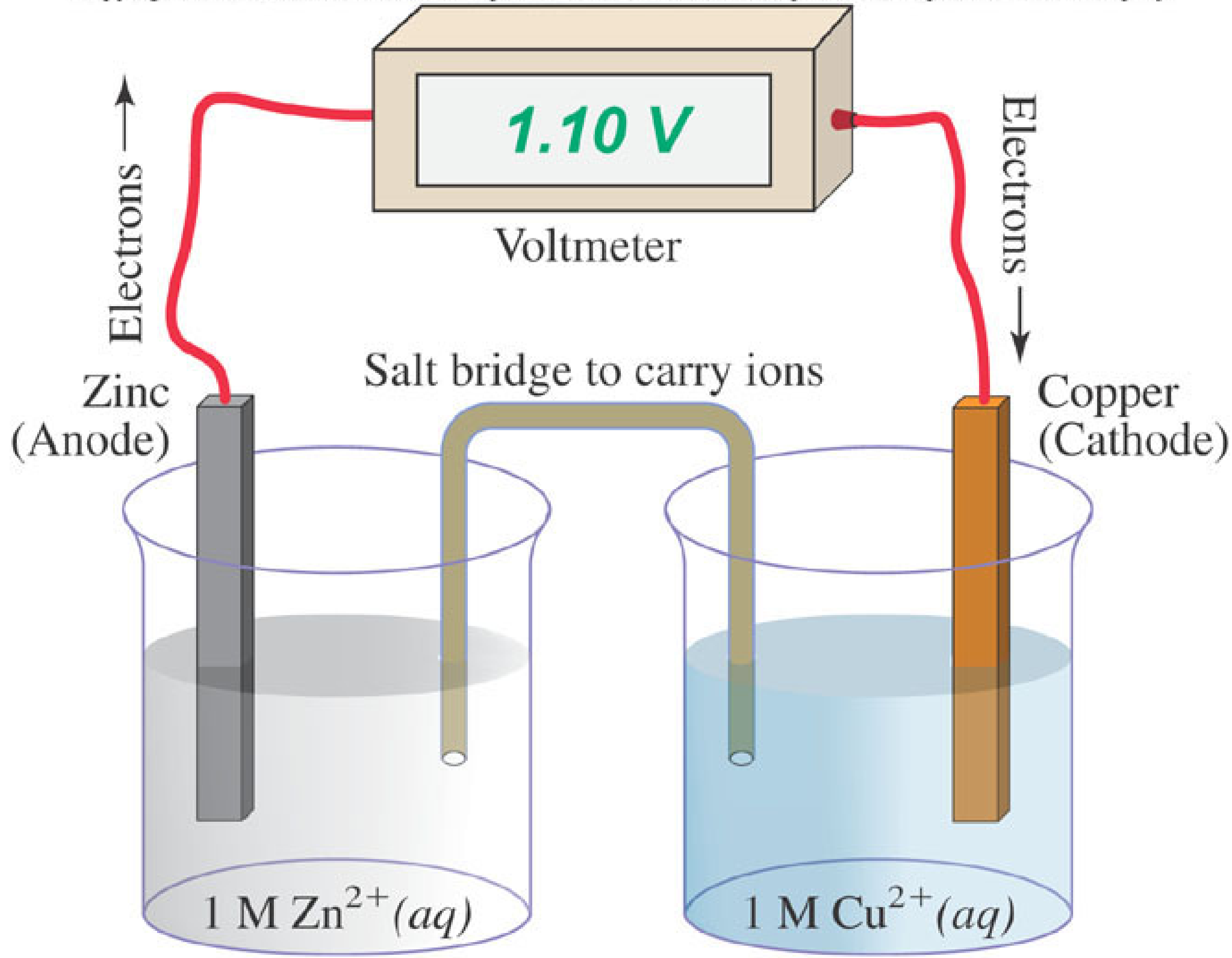


$$Zn(s) + Cu^{2+}(aq) \longrightarrow Zn^{2+}(aq) + Cu(s)$$

$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$	Oxidation	Anode
$Cu^{2+}(aq) + 2e^- \rightarrow Cu(s)$	Reduction	Cathode

Table 8.1 Some Common Galvanic Cells

Type	Voltage	Rechargeable?	Examples of Uses
Alkaline	1.54	No	Flashlights, small appliances
Lithium–iodine	2.8	No	Camera batteries, pacemakers
Lithium ion	3.7	Yes	Laptop computers, cell phones, digital music players
Lead–acid (storage battery)	2.0	Yes	Automobiles
Nickel-cadmium (NiCd)	1.25	Yes	Consumer electronics
Nickel-metal hydride (NiMH)	1.25	Yes	Replacing NiCad for many uses; hybrid vehicles
Mercury	1.3	No	Formerly widely used in cameras, other appliances

Limitations of Traditional Batteries

Eventually, all batteries run down

If they are **not** rechargeable, then they simply run out of material at either the anode or the cathode (or both)

If they **are** rechargeable, then eventually the physical mechanism of keeping products attached to the electrodes fails

Many people believe that this will be the downfall of batteries, and that they will be replaced by something that doesn't ever run down

One such possibility is the Fuel Cell

The Fuel Cell

A Fuel Cell is a galvanic cell which converts the chemical energy from a fuel into electrical energy *without burning the fuel*

Fuel is still *consumed*, but not *combusted*

Sometimes referred to as “flow batteries”, because they must have a constantly replenished flow of both fuel and oxidizer

Fuel cells were invented in 1839 (!), but were just a novelty until there was a reason to worry about combusting fuels…

The U.S. space missions

The Fuel Cell

Fundamentally, a fuel cell is much like a traditional battery

- There are two separate compartments
- Oxidation happens in one, reduction in the other
- Electrons are transferred from one electrode to the other
- *Something* gets consumed… but in a fuel cell, it is immediately replaced

The Fuel Cell

An example fuel cell: the hydrogen fuel cell

Hydrogen is the fuel from which the chemical energy is to be extracted

Oxygen is the oxidant

Anode: $H_2(g) \rightarrow 2\ H^+\ (aq) + 2\ e^-$

Cathode: $\frac{1}{2}\ O_2(g) + 2\ H^+\ (aq) + 2\ e^- \rightarrow H_2O\ (l)$

Net: $\frac{1}{2}\ O_2(g) + H_2(g) \rightarrow H_2O\ (l)$

What could be “cleaner” than that?

Hydrogen’s energy is extracted by interaction with oxygen from the air, and the only product is water

Note that this is the same equation as combustion

The Fuel Cell

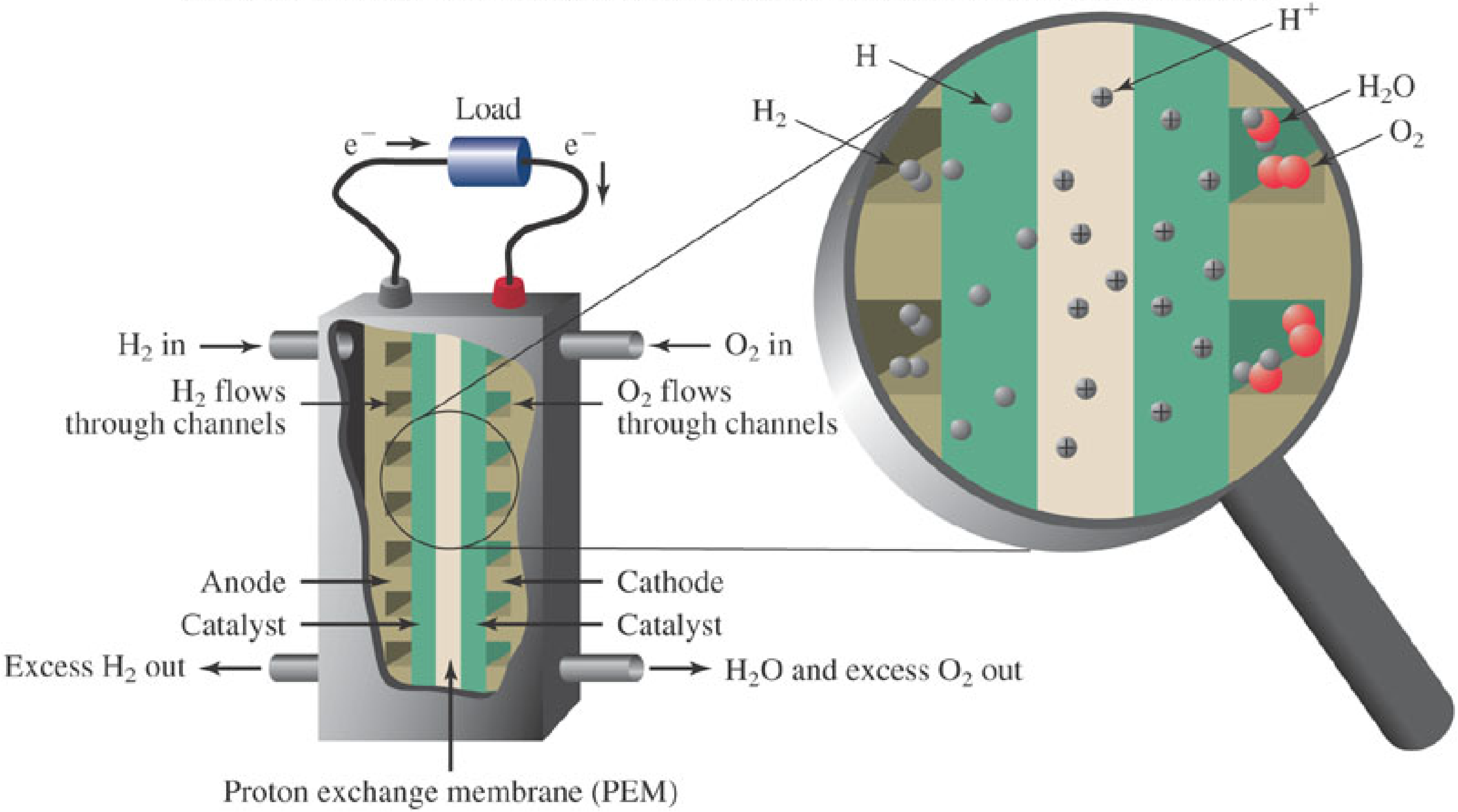
Note that this is the same equation as combustion

But rather than applying a flame, the fuel cell uses a **catalyst** to lower the activation energy of the reaction

Charge is transferred through a **polymer electrolyte membrane** (PEM) also called a **proton exchange membrane**

This membrane has very small holes which are small enough to allow H^+ to pass through, but nothing else

It is coated on both sides with the catalyst – current versions require a platinum catalyst



Anode: $H_2(g) \rightarrow 2\ H^+\ (aq) + 2\ e^-$

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Net: $\frac{1}{2}\ O_2(g) + H_2(g) \rightarrow H_2O\ (l)$

The Fuel Cell

The PEM has to remain moist for the reaction to proceed

Water produced at the anode is recycled to wet the membrane

Operation at high temperatures is difficult, because it is hard to keep the water from evaporating/boiling

Table 8.2 Comparison of Combustion with Fuel Cell Technology

Process	Fuel*	Oxidant	Products	Other Considerations
Combustion	H_2	O_2 from air	H_2O, heat, light, and sound	Rapid process, flame present, lower efficiency, most useful for producing heat
Fuel cell	H_2	O_2 from air	H_2O, electricity, some heat	Slower process, no flame, quiet, higher efficiency, most useful for generating electricity

*Compounds containing hydrogen, such as natural gas or alcohols, can be used as fuels. Since these compounds contain carbon as well, CO or CO_2 (or both) are released as products.

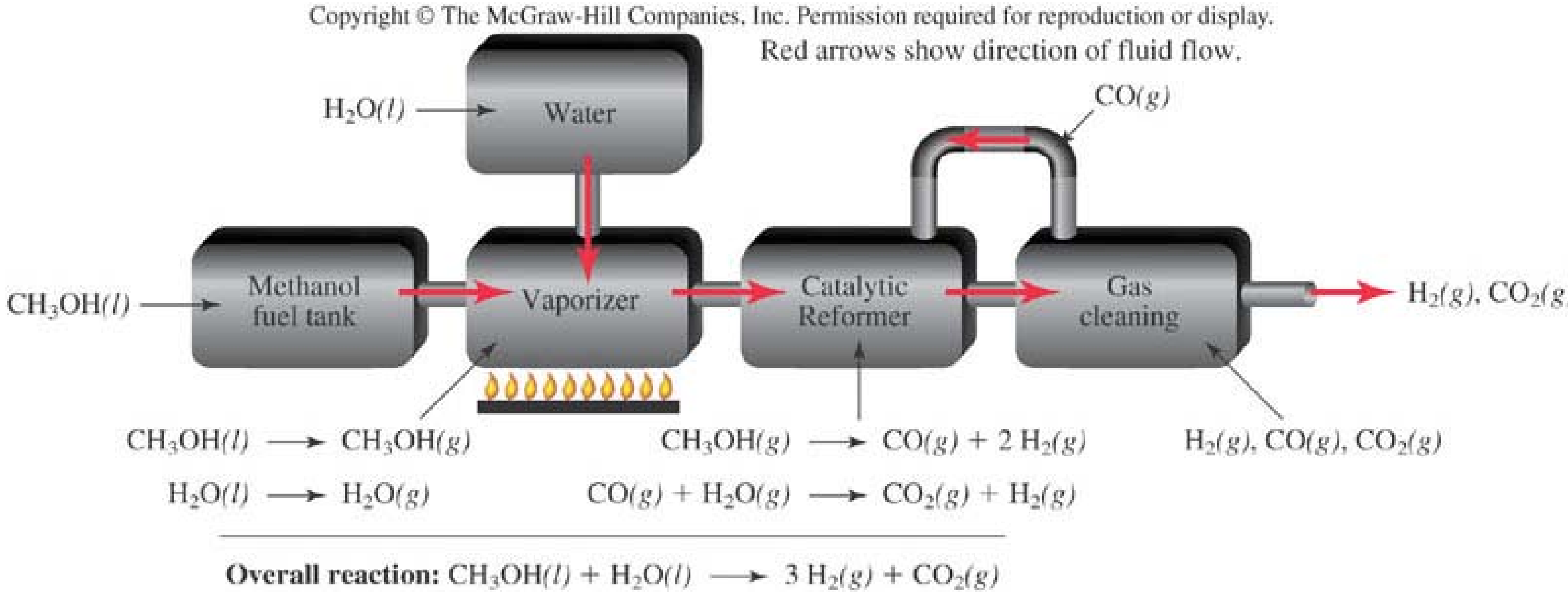
The combustion of H_2 through either method "should" produce 286 kJ/mole

But in both cases, some of that energy is "lost" as heat

In a combustion engine, efficiency is ~ 25%

In a fuel cell, efficiency can be as high as 55%

One obstacle: Where do you get a constantly replenished source of H_2?



One possibility is the extraction of H_2 from methanol (CH_3OH) via the **reforming process**

Other reforming processes exist for gasoline, diesel

The Fuel Cell

The PEM has to remain moist for the reaction to proceed

In addition, the PEM requires platinum as a catalyst

- Platinum is expensive
- Scientists estimate that there is not enough platinum on the planet to build enough fuel cells to replace combustion engines in cars

New models have been proposed using **solid oxide** electrolytes – ZrO_2 and CaO

More resistant to temperature and impurities in fuel

The Fuel Cell: Applications

Distributed generation – providing fuel cells to locations which are not on a standard power grid, or which need backup power for when the grid goes down

- Beginning to flourish in the U.S. and Japan

Cleaner use of fossil fuels

- In Japan, 26% of homes are powered by kerosene power plants
- Using a kerosene reforming process, the same fuel can be used in a zero-emissions* plant
- * - is it really zero-emissions if the by-products include CO_2?

The Fuel Cell: Applications

Microcells may be even closer to widespread application

Some Japanese laptops already run on fuel cell technology

Some predict that they may be in circulation as battery replacements by 2011

Most fuel cell discussions focus on applications in commercial vehicles

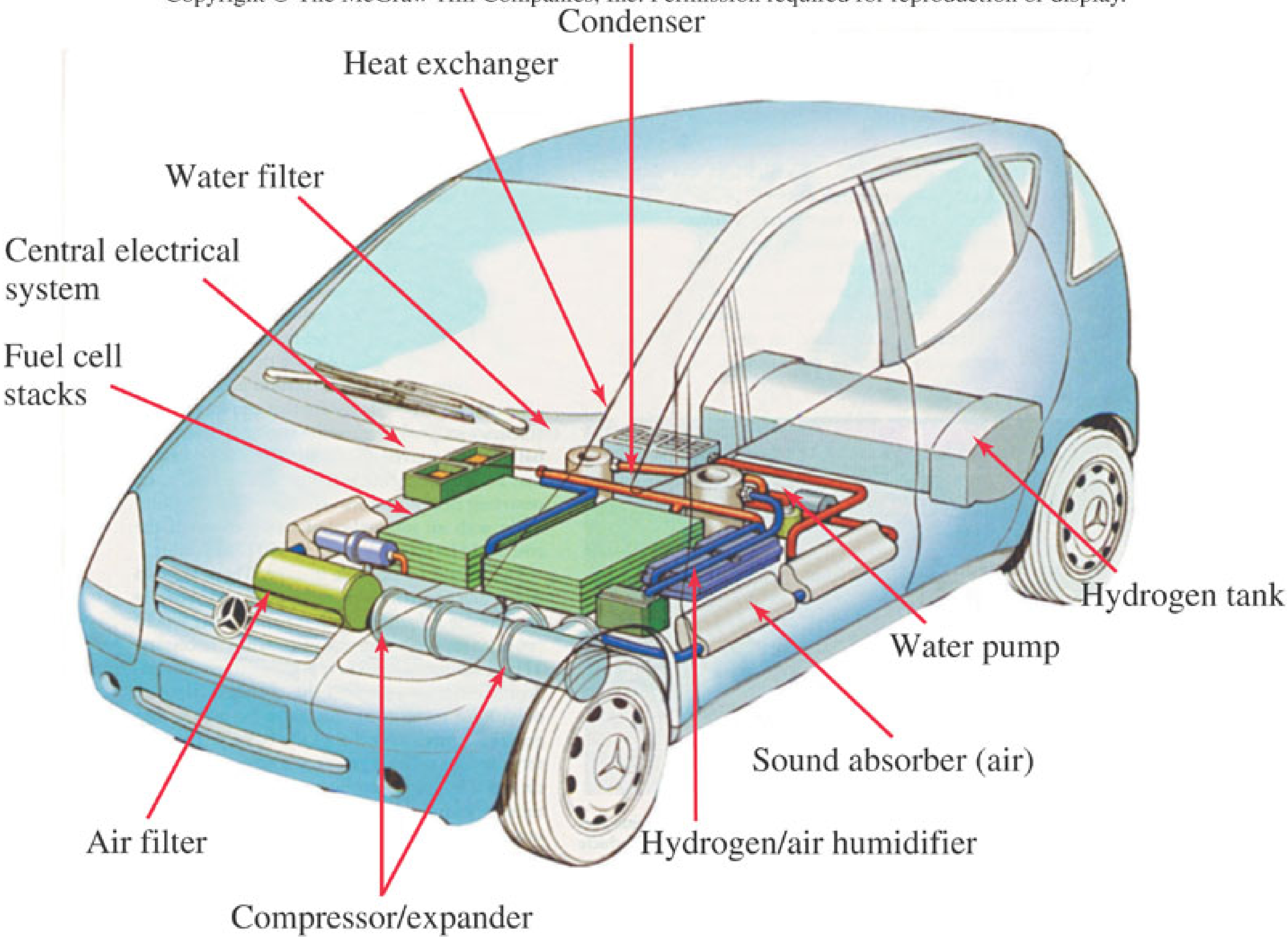
The Fuel Cell: Applications in Motor Vehicles

It is possible to run automobiles on electrical power from hydrogen fuel cells

There have been some holdups in their widespread use

- Safely storing hydrogen gas
- Compactly storing hydrogen gas

But working prototypes exist



Condenser
Heat exchanger
Water filter
Central electrical system
Fuel cell stacks
Hydrogen tank
Water pump
Sound absorber (air)
Air filter
Hydrogen/air humidifier
Compressor/expander

The Fuel Cell: Applications in Motor Vehicles

Other options include on-board reformers to convert methanol to hydrogen as needed

This eliminates the need for bulky/dangerous hydrogen storage

BUT it means that the car is no longer a ZEV

On the other hand…

- The amount of energy per gram of CO_2 is larger
- Engines run at lower T, reducing NO emission
- Methanol is a renewable fuel
- The engine has few moving parts, requires little service

The Electric Car

Electric cars powered by fuel cells are not far off

There are already electric buses in Chicago, D.C. and New York – all using methanol and PEM cells

In 2000, DaimlerChrysler released the New Electric Car 5

- A Mercedes-Benz model run on a methanol fuel cell
- Averages 25 mpg *of methanol*
- Can drive 250 miles without refueling
- Can reach speeds over 90 mph
- Has been driven cross country
- Carries a hefty price tag

The Electric Car

Earlier models had relied solely on the lead storage battery

GM's Saturn EV-1

- Debuted in 1997
- Powered by **26** lead storage batteries...
- ... weighing a total of 1100 pounds
- Developed in response to legislation in California, Massachusetts and New York requiring ZEVs
- (Now mostly repealed, as technology was unprepared)

The Electric Car

GM's Saturn EV-1 was, indeed, a ZEV, but...

- Lead storage batteries struggle at low T
- Recharging the batteries required plugging them in to the power grid
- Local power stations are NOT ZE plants
- In fact, calculations show that while CO2 emissions do go down if lead battery electric cars replace combustion engines...
- ... SO_2 and NO_x go up, due to the additional load at local power plants

So, the future of the electric car must lie elsewhere

Perhaps in the refinement of fuel cell technology, or perhaps in the form of the hybrid vehicle

The Final Exam

May 25th at **9:00 am**

Here!

Letters

Well done!

The average score was 81%

If you scored less than 160/200 on the letter, you may re-submit it

This is entirely optional!

Due our last day of class (May 15)

Turn in your original letter, your original score sheet, and your second draft

You can earn back a maximum of half the points between you and the average score of 162.