Electricity – Innovative Technologies towards Sustainable Development

'Learning-by-Notes' Package for Senior School - Physics

Lesson 8: Fuel Cells

How Do We Make Electricity from Gas?

Teaching Sustainability in High Schools: Subject Supplement

Developed by:

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Here for the future

As part of the:

sustainable Living CHALLENGE

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The Natural Edge Project

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Lesson 8: Fuel Cells

How Do We Make Electricity from Gas?

Bolted under the cargo bay of each NASA space shuttle is a piece of equipment about a metre long. It is shaped like a narrow box and weighs a little over 100 kilograms. This small device is one of the most important items on board the shuttle. If it fails, NASA will call off an entire mission, bringing the crew back to Earth. The function of this device – small enough to fit on your desktop – is power generation. Known as a fuel cell, it efficiently produces enough electricity to run all the equipment on the spacecraft, including the crucial life support systems.[1]

Educational Aim

The aim of this lesson is to describe the key components of fuel cell systems and the process that fuel cell systems use to generate electricity from gas without combustion.

Key Words for Searching Online

Fuel cell systems, fuel cells, fuel cell stack, hydrogen, fuel processors, fuel reformers, electrolysis cells, alkaline fuel cell, proton exchange membrane fuel cell, polymer electrolyte membrane fuel cell, direct alcohol fuel cell, direct methanol fuel cell, direct ethanol fuel cell, phosphoric acid fuel cell, molten carbonate fuel cell, solid oxide fuel cell.

Key Learning Points

1. Fuel cells, like batteries, transform chemical energy into electricity. However, unlike batteries, fuels cells don't store electrical energy. Rather, they convert energy from gases using chemical reactions directly into electrical energy *without combustion*.
2. Mr William Grove produced the first fuel cell in 1839, over 150 years ago. He based his experiment on the fact that sending an electric current through water splits the water into its component parts of hydrogen and oxygen. Grove tried reversing the reaction – combining hydrogen and oxygen to produce electricity and water, which is the basis of a simple fuel cell.[2]
3. Fuel cells are generally comprised of three main components: 1) input gases – a fuel and an oxidant; 2) a fuel processor; and 3) a fuel cell.
4. *Input gases – the fuel:* Most fuel cells use hydrogen as a fuel. Hydrogen makes up 90 percent of the universe and is the third most abundant element on the Earth's surface. Other types of fuel cells use alcohols such as methanol or ethanol as a fuel.

[1] Australian Academy of Science (2008) 'Fuelling the 21st Century' Topic published on the Nova Science in the News website. Available at: http://www.science.org.au/nova/023/023key.htm. Accessed 17 July 2008.
[2] *Ibid.*

5. *Input gases – the oxidant:* Most fuel cells use oxygen as an 'oxidant', taken from the surrounding air. Oxygen makes up 21 percent of the volume of air and 89 percent of the mass of water.

6. *Fuel processor:* This is a device used to create hydrogen gas, because the gas is usually bound with other atoms in the form of a molecule. The two main fuel processing technologies for fuel cell systems are 'fuel reformers' and, less commonly, 'electrolysis cells':

    1. *Fuel reformers*[3] are devices that convert hydrogen-rich fuels into hydrogen gas and carbon compounds – mainly carbon dioxide gas. Fuel reformers also filter out impurities, which reduce the fuel cell's efficiency and life expectancy. *Steam reformers* use heat, pressure and a catalyst.

    2. *Electrolysis cells*[4] are devices that convert water into hydrogen gas and oxygen gas using a process called electrolysis. Electrolysis is the reverse of the process that fuel cells use. There is a new type of electrolysis technology in development that uses about one tenth of the energy used by conventional electrolysis. The new technology uses naturally-occurring bacteria in an electrolysis cell to convert almost any biodegradable, organic materials into hydrogen, pure water and heat.

7. Fuels and oxidants are used in fuel cells to generate electricity as direct current (DC) via a particular type of electrochemical process called an 'oxidation-reduction' reaction.

8. A fuel cell is comprised of two thin, porous electrodes separated by an electrolyte. The electrodes, which incorporate a catalyst, are also connected by an external electric circuit. In a typical fuel cell, hydrogen fuel or hydrogen-rich fuel and oxygen oxidant are combined to generate electricity, heat and pure water vapour. A single fuel cell produces too little electrical power to be of much use, so up to hundreds of fuel cells are linked together in series to form a fuel cell stack.

9. In a typical fuel cell, hydrogen fuel or hydrogen-rich fuel and oxygen oxidant are combined in the presence of a catalyst to generate electricity, heat and pure water vapour via a particular type of electrochemical process called an *oxidation-reduction reaction*. An oxidation-reduction reaction involves an oxidation *half-reaction* at the anode and *reaction half-reaction* at the cathode, and the specific half-reactions vary between the types of fuel cells.

10. Six main types of fuel cells have been developed, with the primary difference between them being the type of electrolyte used. The main differences are that in PEMFCs, DAFCs and PAFCs, positive hydrogen ions flow through the electrolyte, whereas in the AFCs, MCFCs and SOFCs, negative oxygen ions or oxygen-containing ions flow through the electrolyte.

11. Fuel cells are used in a wide variety of applications from powering buildings to cars, buses and space travel. For more information on applications, see the Australian Academy of Science website: http://www.science.org.au/nova/023/023key.htm.

[3] See FuelCellWorks - *Just the Basics on How Fuel Cells Work* at http://www.fuelcellsworks.com/Justthebasics.html. Accessed 25 January 2008; Nice, K. (n.d) *How Fuel Processors Work*, Howstuffworks. Available at http://auto.howstuffworks.com/fuel-processor.htm. Accessed 31 November 2007; Onsite SYCOM Energy Corporation (1999) *Review of Combined Heat and Power Technologies*, US Department of Energy , USA, pp 23-24. Available at http://www.eere.energy.gov/de/pdfs/chp_review.pdf. Accessed 17 April 2007.

[4] See Penn State – *Clean, Carbon-Neutral Hydrogen on the Horizon* at http://www.psu.edu/ur/2007/biohydrogen.htm. Accessed 14 November 2007; Zabarenko, D. (2007) *Waste Water Plus Bacteria Make Hydrogen Fuel: Study*, Reuters, Washington. Available at http://www.reuters.com/article/environmentNews/idUSN1252888620071112. Accessed 14 November 2007.

Brief Background Information

Fuel Cell Systems

Fuel cells are devices that convert gases into electricity without combustion. They generally comprise of three main components.

1. Input gases: a *fuel* and an *oxidant*
2. A *fuel processor*
3. A *fuel cell stack*

Input gases

Hydrogen

Most fuel cells use *Hydrogen* (annotated as 'H' in chemistry) as a fuel. A Hydrogen *atom* consists of one *proton*, one *electron* and one *neutron*. The *stable* hydrogen *molecule* at room temperature and atmospheric pressure is hydrogen *gas*, which consists of two hydrogen atoms as shown in Figure 8.1. Hydrogen makes up 90 percent of the universe and is the third most abundant element on the Earth's surface. However, it is usually bound with other atoms in a molecule so *fuel processing* is usually required.

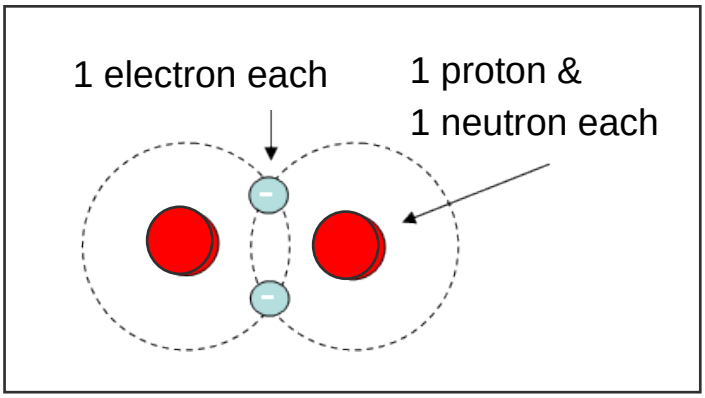


Figure 8.1. Diagram showing the structure of a Hydrogen molecule (2 Hydrogen atoms)

Fundamentals

Atoms are the smallest particles that have the chemical properties of an element. Atoms are comprised of positively-charged *protons*, negatively-charged *electrons*, and zero-charged *neutrons*.

Molecules are the smallest particles that have the chemical properties of a

Alcohol

One type of fuel cell, *direct alcohol fuel cells*, uses alcohols such as *methanol* or *ethanol* as a fuel. Storing a liquid, such as an alcohol, is easier than storing a gas, such as hydrogen.

Oxygen

Most fuel cells use *oxygen* (O) as an oxidant. An oxygen atom consists of eight protons, eight electrons and eight neutrons. The stable oxygen molecule at room temperature and atmospheric pressure is oxygen *gas*, which consists of two oxygen atoms, as shown in Figure 8.2. Oxygen makes up 21 percent of the volume of air and 89 percent of the mass of water. Oxygen used in fuel cells is usually taken from the surrounding air.

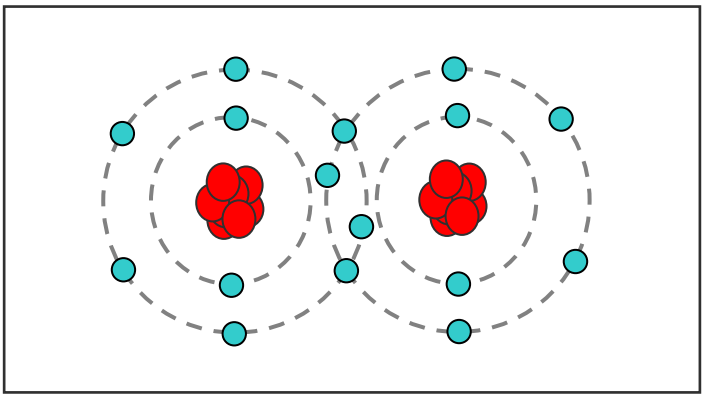


Figure 8.2. Diagram showing the structure of an Oxygen molecule (2 Oxygen atoms)

Fuel Processors

Fuel processors are devices that are used to create hydrogen gas, which is usually bound with other atoms in a molecule. The two main fuel processing technologies for fuel cell systems are 'fuel reformers' and, less commonly, 'electrolysis cells'.

Fuel Reformers

Fuel reformers[5] are devices that convert hydrogen-rich fuels into hydrogen gas and carbon compounds – mainly *carbon dioxide* gas. Currently, the most commonly reformed fuel for fuel cells is called *natural gas*, which is mostly *methane*.[6] Other hydrogen-rich fuels that are reformed include *methanol*, *propane*,

Fundamentals

Chemical potential energy is the energy stored in *chemical bonds* that hold *protons*, *electrons* and *neutrons* together in *atoms*; and that hold atoms together in *molecules*.

Chemical potential energy can be converted to other forms of energy via chemical reactions. For example, chemical potential energy can be converted to *electrical energy* via an *electrochemical reaction*.

[5] See FuelCellWorks - *Just the Basics on How Fuel Cells Work* at http://www.fuelcellsworks.com/Justthebasics.html. Accessed 25 January 2008; Nice, K. (n.d) *How Fuel Processors Work*, Howstuffworks. Available at http://auto.howstuffworks.com/fuel-processor.htm. Accessed 31 November 2007; Onsite SYCOM Energy Corporation (1999) *Review of Combined Heat and Power Technologies*, US Department of Energy , USA, pp 23-24. Available at http://www.eere.energy.gov/de/pdfs/chp_review.pdf. Accessed 17 April 2007.

[6] Wiens, B. (n.d.) *The Future of Fuel Cells*, Ben Wiens Energy Science. Available at http://www.benwiens.com/energy4.html. Accessed 29 January 2008.

butane, *gasoline*, *diesel*, *solid carbon* and *gasified coal*.[7] Fuel reformers also filter out *impurities*. Impurities can bind with a fuel cell's catalyst, a process called *poisoning*, which reduces the fuel cell's efficiency and life expectancy.

In fuel reformers, of which there are several types, the *chemical potential energy* in the output hydrogen gas is about 65 percent of chemical potential energy in the input fuels.[8] This lesson discusses *steam reformers*, of which there are two main types:

1. Natural gas (mostly methane (CH_4)) reformers.
2. Methanol (CH_3OH) reformers. Steam reformers use heat, pressure and a *catalyst* in the processes explained in Table 8.1.

Table 8.1: Processes used in steam reformers to create hydrogen gas from natural gas and methanol

Natural Gas (Methane) Reformer	Methanol Reformer
Water is heated to vapour and is mixed with **natural gas** (mostly **methane**). The vapours pass through a hot chamber that contains a **catalyst**.	**Water** and **methanol**, a liquid, are heated to vapours. The vapours pass through a hot chamber that contains a **catalyst**.
The methane in the methane and water vapour react to form **carbon monoxide** and **hydrogen gas**. $CH_4 + H_2O \rightarrow CO + 3H_2$	The catalyst causes the methanol to separate into **carbon monoxide** and **hydrogen gas**. $CH_3OH \rightarrow CO + 2H_2$
The catalyst causes the water vapour to separate into **hydrogen gas** and an **oxygen atom**. $H_2O \rightarrow H_2 + O$	The catalyst causes the water vapour to separate into **hydrogen gas** and an **oxygen atom**. $H_2O \rightarrow H_2 + O$
The carbon monoxide and oxygen atom react to form **carbon dioxide**. $CO + O \rightarrow CO_2$	The carbon monoxide and oxygen atom react to form **carbon dioxide**. $CO + O \rightarrow CO_2$

Source: Nice, K. (n.d)[9]

Fuel cells that operate at high temperature, such as *molten carbonate fuel cells* and *solid oxide fuel cells*, usually reform fuels internally and so do not require an external fuel reformer. Also, *direct alcohol fuel cells* use alcohols such as methanol or ethanol as a fuel and so do not require the fuel to be reformed either.

Electrolysis Cells

Electrolysis cells[10] are devices that convert water into hydrogen gas and oxygen gas using a process called *electrolysis*. Electrolysis is the reverse of the process that fuel cells use. In

[7] California Energy Commission (2003) *Distributed Energy Resource Guide: Fuel Cells*, State of California Government, USA. Available at www.energy.ca.gov/distgen/equipment/fuel_cells/fuel_cells.html. Accessed 17 November 2007; See FuelCellWorks - *Just the Basics on How Fuel Cells Work* at http://www.fuelcellsworks.com/Justthebasics.html. Accessed 25 January 2008; Buchmann, I. (2003) *The Fuel Cell*, Battery University. Available at http://www.batteryuniversity.com/parttwo-52.htm. Accessed 29 January 2008.

[8] Wiens, B. (n.d.) *The Future of Fuel Cells*, Ben Wiens Energy Science. Available at http://www.benwiens.com/energy4.html. Accessed 29 January 2008.

[9] Nice, K. (n.d) *How Fuel Processors Work*, Howstuffworks. Available at http://auto.howstuffworks.com/fuel-processor.htm. Accessed 31 November 2007.

conventional electrolysis cells, the chemical potential energy in the resulting hydrogen gas is 50-70 percent of the electrical energy applied.

Of course, there is no extra energy value in using conventionally-generated electricity to create hydrogen and then reversing the process to use that hydrogen to generate the same quantity of electricity!

However, there is an application for this arrangement in *regenerative fuel cells*. Regenerative fuel cells are valuable when electricity is required for 24 hours per day but only available for part of the day. For example, in remote areas where only solar-generated electricity is available, electrolysis can be used to create hydrogen gas and oxygen gas during the day and a fuel cell can be used to generate electricity at night.

There is a new type of electrolysis technology in development that uses about one tenth of the energy used by conventional electrolysis. The new technology uses naturally-occurring bacteria in an electrolysis cell to convert almost any biodegradable, organic materials into hydrogen, pure water and heat in the following process:

- The bacteria consume the organic material and release protons and electrons, creating up to 0.3 volts. (The bacteria do the work of a large portion of the electricity used in a conventional electrolysis cell.)
- More than 0.2 volts are applied externally, which provides enough energy for the protons and electrons to combine and form hydrogen gas molecules.

In an electrolysis cell that uses acetic acid (found in vinegar and from glucose and cellulose fermentation) as the organic material, the chemical potential energy in the output hydrogen gas is 288 percent of the input electrical energy. When considering the total input energy – both the energy in the electricity and the chemical potential energy in the acetic acid – the hydrogen gas contains 82 percent of the total input energy. In other electrolysis cells that use lactic acid, cellulose or glucose as the organic material, the output hydrogen contains 62-82 percent of the total input energy.

Fuel Cell Stack

Fuels and oxidants are used in fuel cells to generate electricity as direct current (DC) via an *electrochemical process*, similar to that in a battery. The main difference is that in a fuel cell, the fuel and oxidant supply is external and replenished. In a battery, the fuel and oxidant supply is stored and limited.

A fuel cell is comprised of two thin, porous *electrodes* separated by an *electrolyte*. The electrodes, which incorporate a catalyst, are also connected by an *external electric circuit* (see Figure 8.3):[11]

Fundamentals

A *catalyst* is a substance that increases the speed of a chemical reaction by decreasing the energy required to break and form chemical bonds. Catalysts are not part of the reaction and thus are not altered.

[10] See Penn State – *Clean, Carbon-Neutral Hydrogen on the Horizon* at http://www.psu.edu/ur/2007/biohydrogen.htm. Accessed 14 November 2007; Zabarenko, D. (2007) *Waste Water Plus Bacteria Make Hydrogen Fuel: Study*, Reuters, Washington. Available at http://www.reuters.com/article/environmentNews/idUSN1252888620071112. Accessed 14 November 2007.

[11] Nice, K. and Strickland, J. (n.d) *How Fuel Cells Work*, Howstuffworks. Available at http://auto.howstuffworks.com/fuel-cell.htm. Accessed 14 November 2007.

- *Anode* (negative electrode): has channels that distribute the fuel over the catalyst evenly and conducts the electrons from the catalyst to the external electric circuit.
- *Cathode* (positive electrode): has channels that distribute the oxidant over the catalyst evenly and conducts the electrons from the external circuit to the catalyst.
- *Electrolyte*: is a solid or solution that has a voltage across it and that facilitates in the flow of positive or negative ions from one electrode to the other while blocking electrons.
- *Catalyst*: is usually platinum or a nickel-platinum alloy[12] that is applied on the electrodes in a thin, rough, porous coat for maximum surface area and enhances the electrochemical process.
- *External electric circuit:* includes a current conditioner or load and carries electrons from the anode to the cathode.

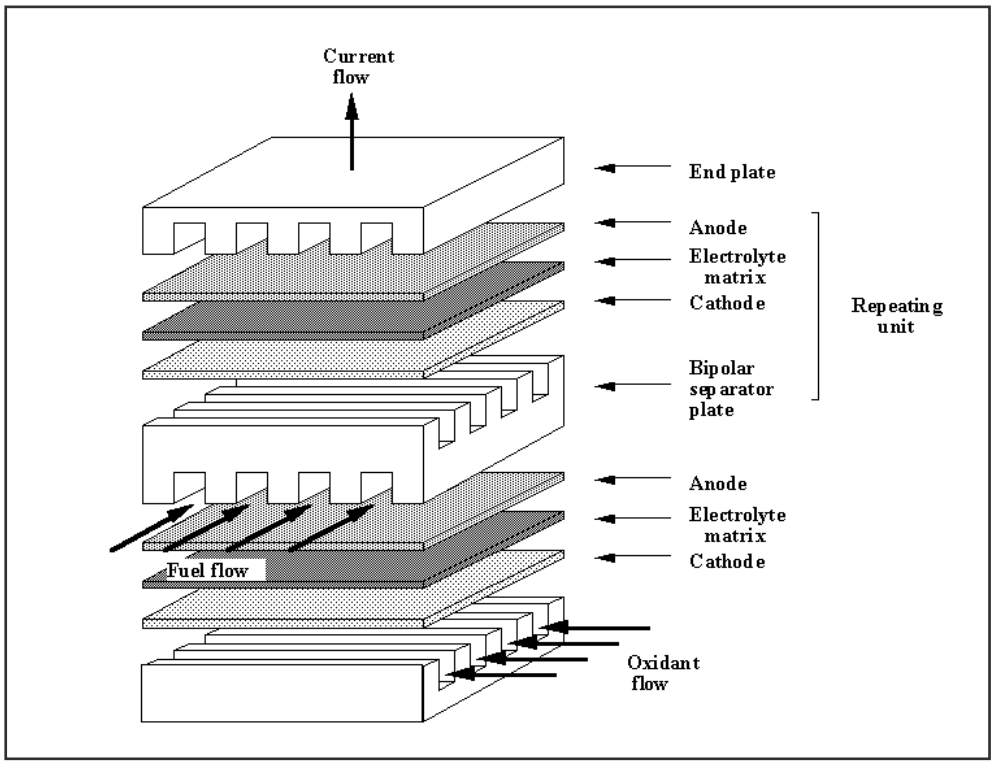


Figure 7.1. Exploded view of a fuel cell in a fuel cell stack

Source: Kinoshita, K. (2001)[13]

Fuel cells convert 20-60 percent of the input chemical potential energy into output *electrical energy*. A single fuel cell produces 0.5-0.9 volts under load, which is too low to be of much use.[14] Up to hundreds of fuel cells are linked together in series to form a fuel cell stack, which

[12] Research Institute for Sustainable Energy (2006) *Fuel Cells*, Murdoch University. Available at http://www.rise.org.au/info/Tech/fuelcells/index.html. Accessed 14 November 2007.
[13] Kinoshita, K. (2001) 'Electrochemical Uses of Carbon' in *Electrochemistry Encyclopedia*, Case Western Reserve University, Cleveland. Available at http://electrochem.cwru.edu/ed/encycl/index.html. Accessed 3 February 2008.
[14] Buchmann, I. (2003) *The Fuel Cell*, Battery University. Available at http://www.batteryuniversity.com/parttwo-52.htm. Accessed 29 January 2008; Nice, K. and Strickland, J. (n.d) *How Fuel Cells Work*, Howstuffworks. Available at http://auto.howstuffworks.com/fuel-cell.htm. Accessed 14 November 2007; Onsite SYCOM Energy Corporation (1999) *Review of Combined Heat and Power Technologies*, US Department of Energy , USA, p 23. Available at http://www.eere.energy.gov/de/pdfs/chp_review.pdf. Accessed 17 April 2007.

can generate a useful amount of voltage and power. A fuel cell stack's power output can range from 1 kilowatt to 11 megawatts (see Table 8.3).

In a typical fuel cell, hydrogen fuel or hydrogen-rich fuel and oxygen oxidant are combined in the presence of a catalyst to generate electricity, heat and pure water vapour via a particular type of electrochemical process called an *oxidation-reduction reaction*. An oxidation-reduction reaction involves an *oxidation half-reaction* at the anode and *reaction half-reaction* at the cathode, and the specific half-reactions vary between the types of fuel cells. Six main types of fuel cells have been developed, with the primary difference between them being the type of electrolyte used (see Table 8.3 for details regarding the specific electrolytes):

1. *Alkaline fuel cell* (AFC)
2. *Proton exchange membrane fuel cell* or *polymer electrolyte membrane fuel cell* (PEMFC)
3. *Direct alcohol fuel cell* (DAFC),[15] also known as *direct methanol* (DMFC) or *direct ethanol* (DEFC) *fuel cell*, depending on the fuel used
4. *Phosphoric acid fuel cell* (PAFC)
5. *Molten carbonate fuel cell* (MCFC)
6. *Solid oxide fuel cell* (SOFC)

The main differences are that in PEMFCs, DAFCs and PAFCs, positive *hydrogen ions* flow through the electrolyte, whereas in the AFCs, MCFCs and SOFCs, negative *oxygen ions* or oxygen-containing ions flow through the electrolyte. The overall processes for the simplest reactions are explained in Table 8.2, and the half reactions and full reactions are given in Table 8.3. In some types of fuel cell, ions other than hydrogen ions or oxygen ions transfer across the electrolyte. For example, AFCs use hydroxyl ions (OH^-) and MCFCs use carbonates (CO_3^{2-}). For an animation of a PEMFC in operation, see Nice, K. and Strickland, J. (n.d).[16]

[15] Direct alcohol fuel cells are a type of proton exchange membrane fuel cell.
[16] Nice, K. and Strickland, J. (n.d) *How Fuel Cells Work*, Howstuffworks. Available at http://auto.howstuffworks.com/fuel-cell.htm. Accessed 14 November 2007.

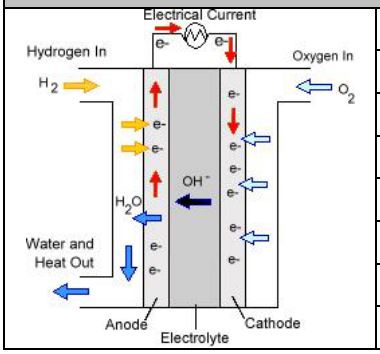
Table 8.2: Processes used in fuel cells to generate electricity

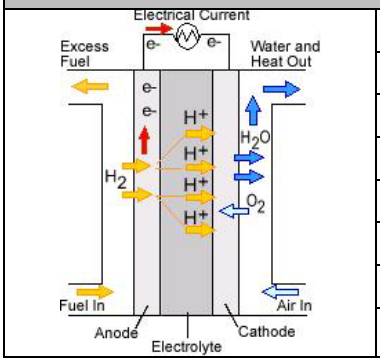
PEMFC, DAFC and PAFC (Hydrogen ions flow through the electrolyte)	AFC, MCFC and SOFC (Oxygen ions flow through the electrolyte)
At the anode, **hydrogen gas** (molecule) or **hydrogen-rich gas** (molecule) is fed through the **catalyst**. The catalyst causes the hydrogen molecule to separate into two **electrons** and two **hydrogen ions**.	At the anode, **hydrogen gas** (molecule) is fed through the **catalyst**. The catalyst causes the hydrogen molecule and **oxygen ions** (created at the cathode) to combine to create **water**, **electrons** and **heat**.
The electrons are attracted to the positively-charged cathode, but the electrolyte only permits positive ions to pass and blocks electrons. Therefore, the electrons flow through the external electric circuit, which includes the load. This flow of electrons is **electricity**.	The electrons are attracted to the positively-charged cathode, but the electrolyte only permits negative ions to pass and blocks electrons. Therefore, the electrons flow through the external electric circuit, which includes the load. This flow of electrons is **electricity**.
The cathode now has an excess of negative charges. Therefore, the hydrogen ions are attracted to the cathode. The hydrogen ions flow from the anode, through the **electrolyte**, to the cathode.	At the cathode, **oxygen gas** (molecule) is fed through the catalyst. The catalyst causes the oxygen to combine with electrons to create oxygen ions.
At the cathode, **oxygen gas** (molecule) is fed through the catalyst. The catalyst causes the hydrogen ions, oxygen molecules and electrons to combine to create **water** and **heat**.	The cathode now has an excess of negative charges. Therefore, the oxygen ions are attracted to the anode. The oxygen ions flow from the cathode, through the **electrolyte**, to the anode.

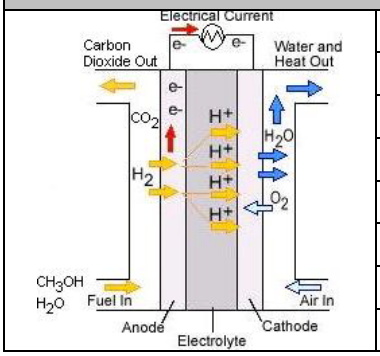
Source: Research Institute for Sustainable Energy (2006)[17] and US Department of Energy[18]

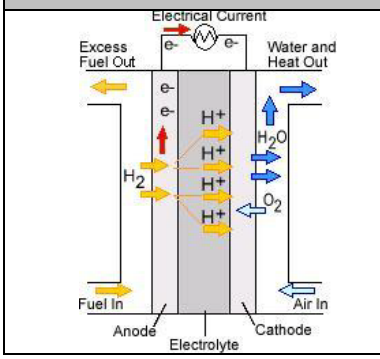
[17] Research Institute for Sustainable Energy (2006) *Fuel Cells*, Murdoch University. Available at http://www.rise.org.au/info/Tech/fuelcells/index.html. Accessed 14 November 2007.
[18] See US Department of Energy – *Types of Fuel Cells* at http://www1.eere.energy.gov/hydrogenandfuelcells/fuelcells/fc_types.html. Accessed 3 February 2008.

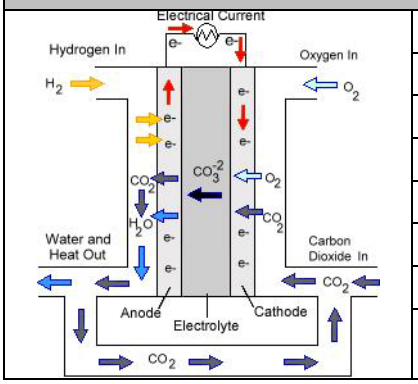
Table 8.3: Characteristics of the six main types of fuel cells

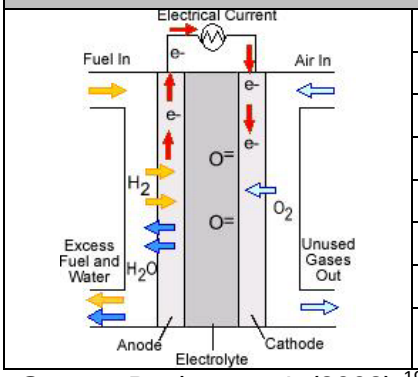
Alkaline Fuel Cell		
	*Electrolyte:*	Potassium hydroxide (KOH)
	Anode:	$4OH^- + 2H_2 \rightarrow 4H_2O + 4e^-$
	Cathode:	$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
	Overall:	$2H_2 + O_2 \rightarrow 2H_2O$
	Temperature:	50-250ºC
	Capacity:	n/a
	Efficiency:	60%
	Applications:	Space vehicles, submarines

Proton Exchange Membrane Fuel Cell		
	*Electrolyte:*	Thin, solid, organic polymer
	Anode:	$2H_2 \rightarrow 4H^+ + 4e^-$
	Cathode:	$O_2 + 4H^+ + 4e^- \rightarrow 2H_20$
	Overall:	$2H_2 + O_2 \rightarrow 2H_2O$
	Temperature:	50-100ºC
	Capacity:	3-250 kW
	Efficiency:	25-50%
	Applications:	Cars, buses, medium-large-scale power generation

Direct Alcohol (Methanol CH_3OH) Fuel Cell		
	*Electrolyte:*	Thin polymer
	Anode:	$CH_3OH + H_2O \rightarrow CO_2 + 6H^+ + 6e^-$
	Cathode:	$3/2\ O_2 + 6H^+ + 6e^- \rightarrow 3H_2O$
	Overall:	$CH_3OH + 3/2\ O_2 \rightarrow CO_2 + 2H_2O$
	Temperature:	50-100ºC
	Capacity:	3-250 kW
	Efficiency:	20-40%
	Applications:	Cars, buses, appliances, small-scale power

Phosphoric Acid Fuel Cell		
	*Electrolyte:*	Phosphoric acid liquid (H_3PO_4)
	Anode:	$2H_2 \rightarrow 4H^+ + 4e^-$
	Cathode:	$O_2 + 4H^+ + 4e^- \rightarrow 2H_20$
	Overall:	$2H_2 + O_2 \rightarrow 2H_2O$
	Temperature:	160-220ºC
	Capacity:	100 kW-11 MW
	Efficiency:	36-45%
	Applications:	Medium-large-scale power generation

Molten Carbonate Fuel Cell		
	*Electrolyte:*	Carbonates (CO_3^{2-}) of lithium, sodium or potassium
	Anode:	$H_2 + CO_3^{2-} \rightarrow H_2O + CO_2 + 2e^-$
	Cathode:	$½\ O_2 + CO_2 + 2e^- \rightarrow CO_3^{2-}$
	Overall:	$H_2 + ½\ O_2 + CO_2 \rightarrow H_2O + CO_2$
	Temperature:	600-650ºC
	Capacity:	250 kW-10 MW
	Efficiency:	45-55%
	Applications:	Large-scale power generation

Solid Oxide Fuel Cell		
	*Electrolyte:*	Hard, non-porous ceramic
	Anode:	$H_2 + O^{2-} \rightarrow H_2O + 2e^-$
	Cathode:	$½\ O_2 + 2e^- \rightarrow O^{2-}$
	Overall:	$H_2 + ½\ O_2 \rightarrow H_2O$
	Temperature:	500-1000ºC
	Capacity:	1 kW-10 MW
	Efficiency:	45-60%
	Applications:	Small-large-scale power generation

Source: Buchmann, I. (2003),[19] California Energy Commission (2003),[20] FuelCellWorks,[21] Onsite SYCOM Energy Corporation (1999),[22] Research Institute for Sustainable Energy (2006),[23] US Department of Energy,[24] Wiens, B. (n.d.)[25]

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