

FUEL CELLS

Fuel cell:

A specialised galvanic cell that generates electricity from the oxidation of a fuel by oxygen (usually sourced from air).

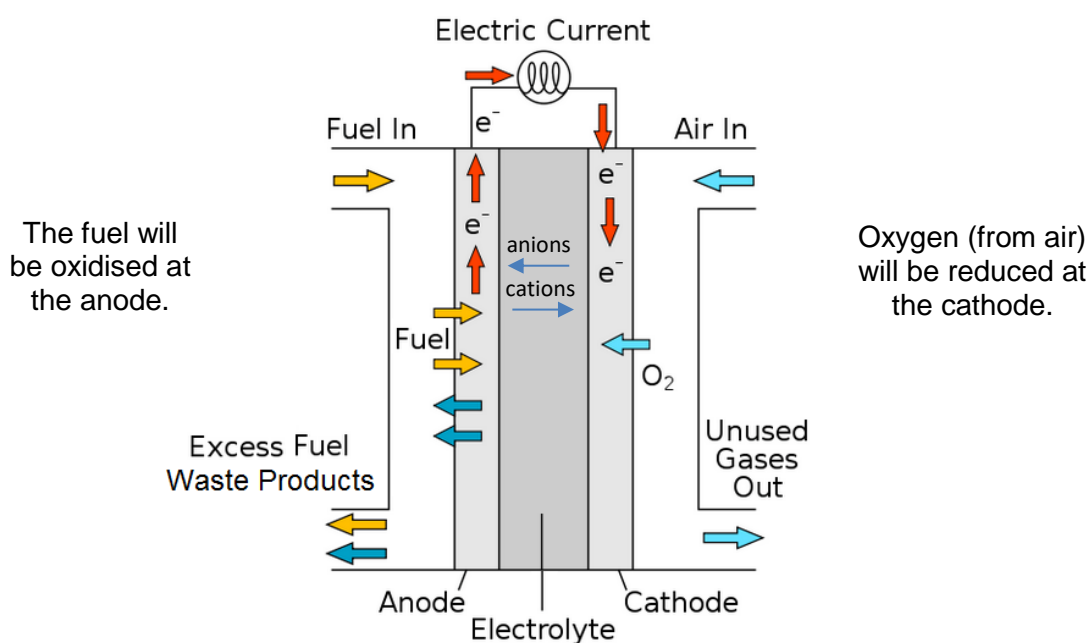
Differences between a fuel cell and a primary or secondary cells include:

- Reactants are continuously fed into the system.
- Products are continuously removed from the system.
- A continuous supply of electrical energy is produced.
- Fuel cells never become flat and don't need recharging.

Fuel cells contain the same basic components as all other galvanic cells.

- Anode and cathode (separated from one another).
- Electrolyte (which acts like a salt bridge).
- An external circuit.

The electrons produced via oxidation at the anode travel through the external circuit to the cathode where they are consumed via reduction.



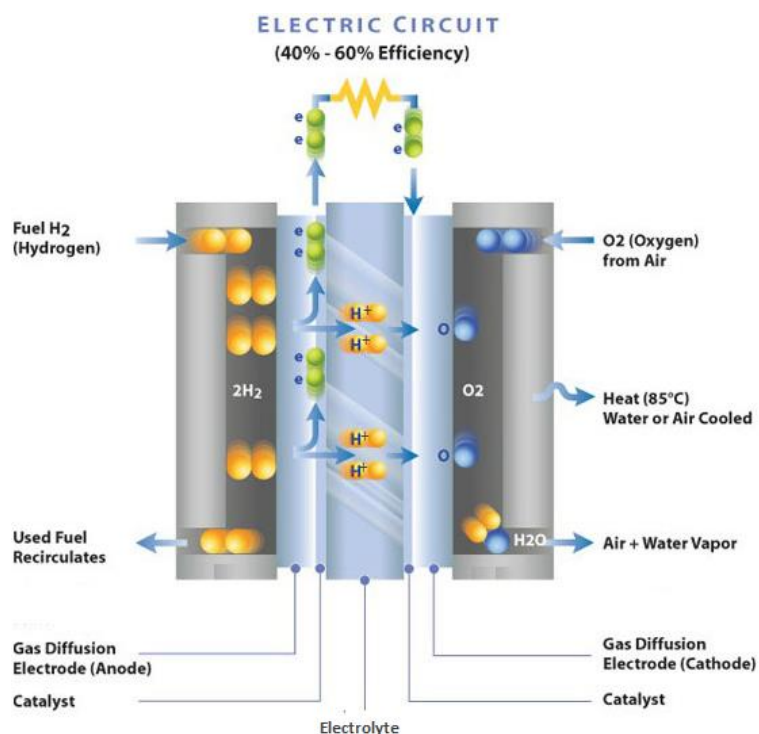
- Oxidation occurs at the anode (-ve).
- Reduction occurs at the cathode (+ve).
- Electrons flow from anode to cathode through the external circuit.
- A layer of electrolyte acts as the salt bridge – it allows for the movement of charge through the cell.
- Chemical energy is converted into electrical energy.

SPECIFIC FUEL CELL DESIGN

All fuel cells share the same basic setup.

Every fuel cell requires:

- Porous, catalytic electrodes.
- An electrolyte.
- Auxillary systems.



Auxillary Systems:

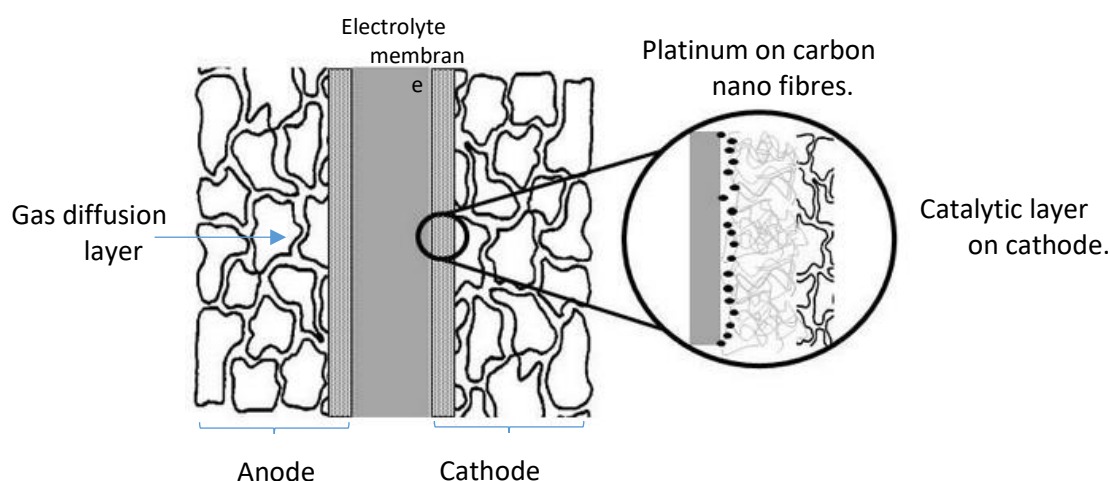
Auxillary systems are needed for:

- Fuel delivery to the anode.
- Oxygen delivery to the cathode.
- Removal waste products.
- Maintenance of operating temperatures.

The running costs involved with these systems is one of the drawbacks of fuel cell technology.

Electrodes:

- Provide a surface on which oxidation and reduction can take place.
- Must be conductive so that electrons will flow through them.
- Must be highly porous to provide a large surface area for gases disperse into and react on. This improves the efficiency of the cell by allowing larger currents to be generated.
- Are coated in a catalyst (commonly Pt on a carbon support) to lower the activation energy required for the reactions to take place.
- Must be stable to avoid deterioration of the electrodes and loss of catalytic surfaces.
- May need to withstand high temperatures.



Note:

The electrodes are generally made of two layers. A gas diffusion layer to encourage the gaseous reactants to penetrate the electrode and a catalytic layer where the redox reactions take place.

Electrolyte:

The purpose of the electrolyte is to allow for the movement of ions through the internal circuit of the fuel cell. Electrolytes come in a variety of forms: aqueous solutions, solid oxide or molten carbonate are just a few. Some fuel cells use polymer electrolyte membranes (PEM). These membranes conduct ions such as hydrogen ions but not electrons nor the gaseous reactants. The membranes need to be unreactive so that they don't become damaged in oxidizing/reducing environments around the electrodes.

Fuel cells are classified by the type of **electrolyte** they use. The main types of electrolyte are:

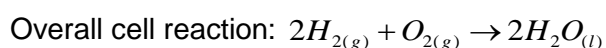
| Fuel cell | Electrolyte |
|--------------------------------|---|
| Acidic | H^+ ions |
| Alkaline | OH^- ions |
| Solid oxide | O^{2-} ions |
| Proton Exchange Membrane (PEM) | Polymer membrane with solid polyperfluorosulfonic acid which allows H^+ ion transfer. |
| Phosphoric Acid | H_3PO_4 (liquid) |
| Molten Carbonate | CO_3^{2-} ions from molten carbonate salts which move through a ceramic matrix. |
| Direct Methanol | Polymer membrane which allows H^+ ion transfer |

The type of electrolyte also dictates a cell's operating temperature—"molten" carbonate cells run hot, just as the name implies.

PREDICTING CELL REACTIONS

The half cell reactions that occur in a fuel cell will be influenced by the type of electrolyte used.

For example, a number of different electrolytes can be used in hydrogen – oxygen fuel cells. These include, acidic, basic, molten carbonate and oxide electrolytes. In each case, the half equations will be different even though the overall cell reaction will be the same.



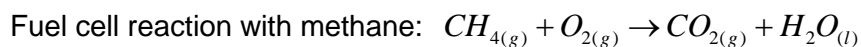
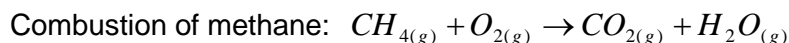
Half Cell reactions:

| Electrolyte | Anode | Cathode |
|-------------|---|--|
| Acidic | $H_{2(g)} \rightarrow 2H_{(aq)}^+ + 2e^-$ | $O_{2(g)} + 4H_{(aq)}^+ + 4e^- \rightarrow 2H_2O_{(l)}$ |
| Alkaline | $H_{2(g)} + 2OH_{(aq)}^- \rightarrow 2H_2O_{(l)} + 2e^-$ | $O_{2(g)} + 2H_2O_{(l)} + 4e^- \rightarrow 4OH_{(aq)}^-$ |
| Solid oxide | $H_{2(s)} + O_{in\ ceramic}^{2-} \rightarrow H_2O_{(l)} + 2e^-$ | $O_{2(g)} + 4e^- \rightarrow 2O_{in\ ceramic}^{2-}$ |

Note that in all the fuel cells listed in the table above, the electrolyte ion appears in both half equations. This can be useful to remember when you are trying to balance half equations, particularly for fuel cells with unusual electrolytes.

When fuels other than hydrogen are used then the overall equation is often the same as the combustion of that fuel. However, the water produced is most likely to be a liquid.

For example:



Once the overall equation is known, it can be used to determine the half equations keeping in mind that the electrolyte ion is probably going to appear in both half equations.

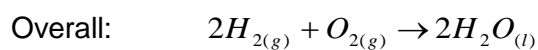
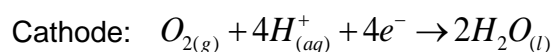
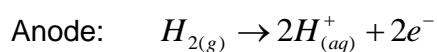
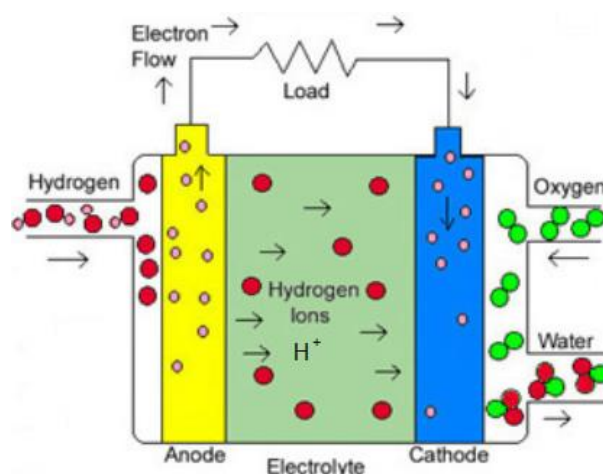
Other fuels that can be used in fuel cells include:

- Methanol
- Biogas
- Natural Gas
- Glucose

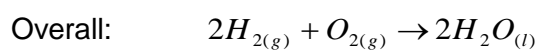
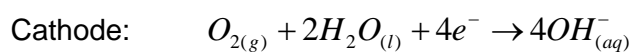
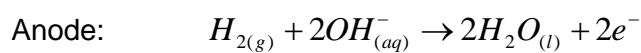
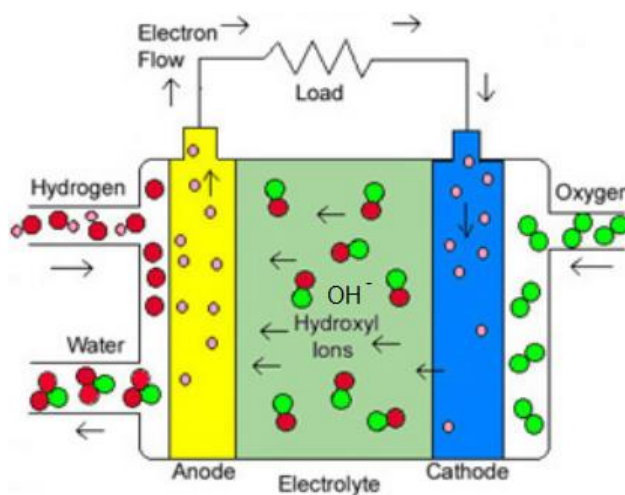
Hints:

- If the cell is acidic, balance using the usual rules.
- If the cell is alkaline, balance using the usual rules and then adjust for the alkaline environment.
- If the electrolyte is not acidic or alkaline then more problem solving will be needed! Remember – the electrolyte ion will appear in both half equations!
- If a non-hydrogen fuel is used, the overall equation is often the same as for the combustion of the fuel although the state of water may be different.

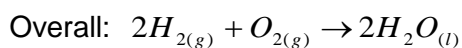
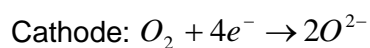
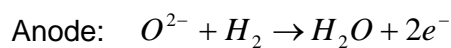
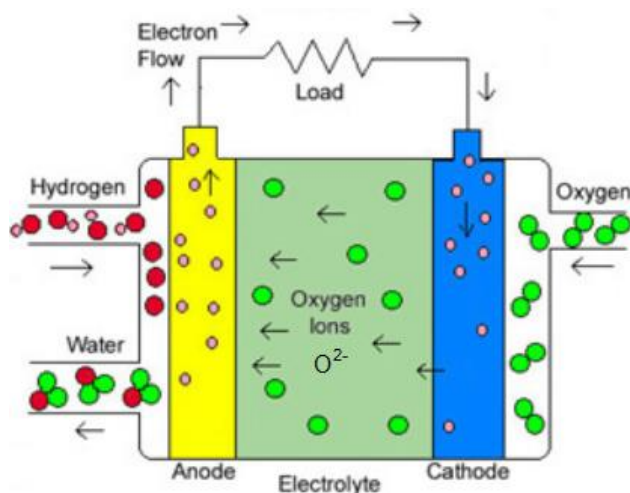
ACIDIC, PHOSPHORIC ACID, PEM



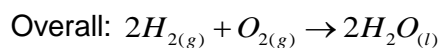
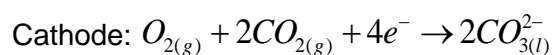
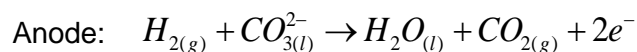
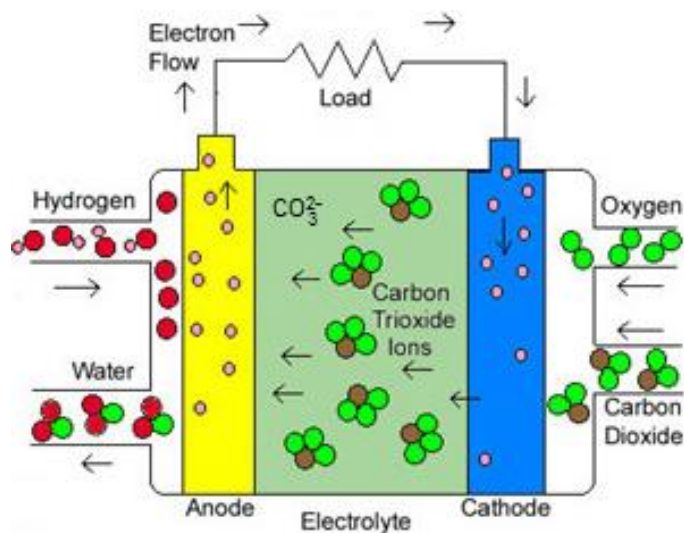
ALKALINE



SOLID OXIDE

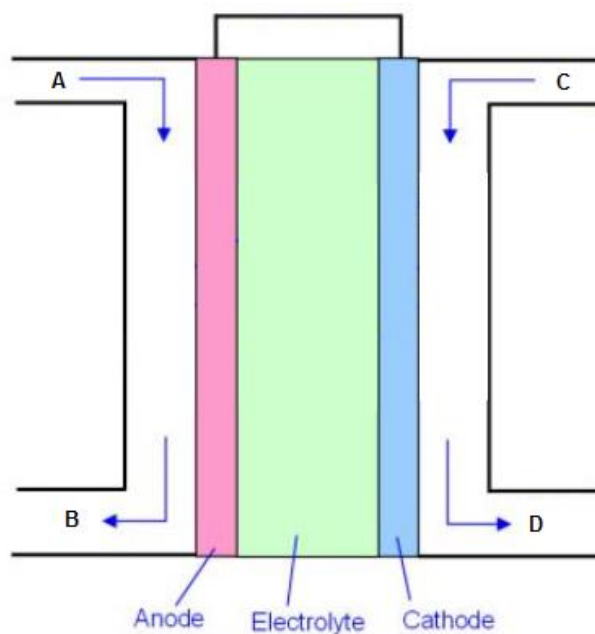


MOLTEN CARBONATE



Note: Anions in electrolyte move towards the anode, cations move towards the cathode.

Use the diagram below of a molten carbonate fuel cell to answer the following questions.



QUESTION 30

The fuel used in the cell is most likely to be:

- A Hydrogen
- B Oxygen
- C Water
- D Carbonate ions

QUESTION 31

The oxidant would enter at:

- A A
- B B
- C C
- D D

QUESTION 32

The substances at B would be:

- A Water and carbon dioxide
- B Water
- C Carbon dioxide
- D Carbonate ions

QUESTION 33

The electrolyte used would be:

- A Hydrogen ions
- B Hydroxide ions
- C Solid oxide ions
- D Carbonate ions

QUESTION 34

In this fuel cell:

- A The electrolyte would move from cathode to anode and the electrons would move from anode to cathode.
- B The electrolyte would move from anode to cathode and the electrons would move from anode to cathode.
- C The electrolyte would move from cathode to anode and the electrons would move from cathode to anode.
- D The electrolyte would move from anode to cathode and the electrons would move from cathode to anode.

QUESTION 35

The mole of electrons consumed at the cathode would be:

- A 4 mol
- B Double the mole produced at the anode.
- C Half the mole produced at the anode.
- D The same as the mole produced at the anode.

QUESTION 36

This fuel cell differs from alkaline or acidic fuel cells because:

- A It uses different fuels
- B The electrolyte is in a different state
- C The electrolyte ion moves to the electrode of the same charge.
- D It produces different by-products.

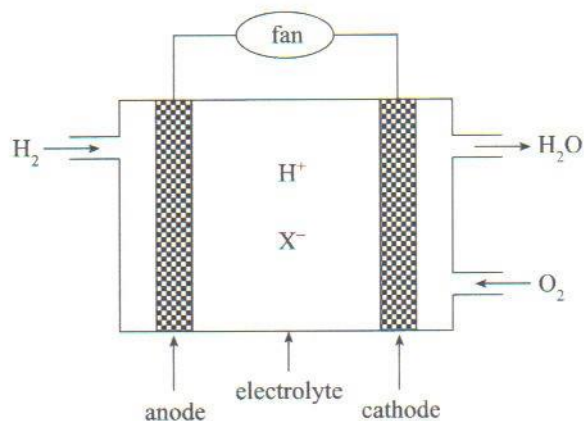
QUESTION 37

Compared to a fuel cell which uses methane, a hydrogen – oxygen molten carbonate fuel cell would:

- A Produce no carbon dioxide
- B Produce slightly less carbon dioxide
- C Produce much less carbon dioxide
- D Produce slightly more carbon dioxide

QUESTION 38

Fuel cells use hydrogen as a fuel to produce energy. A diagram of a fuel cell is shown below:



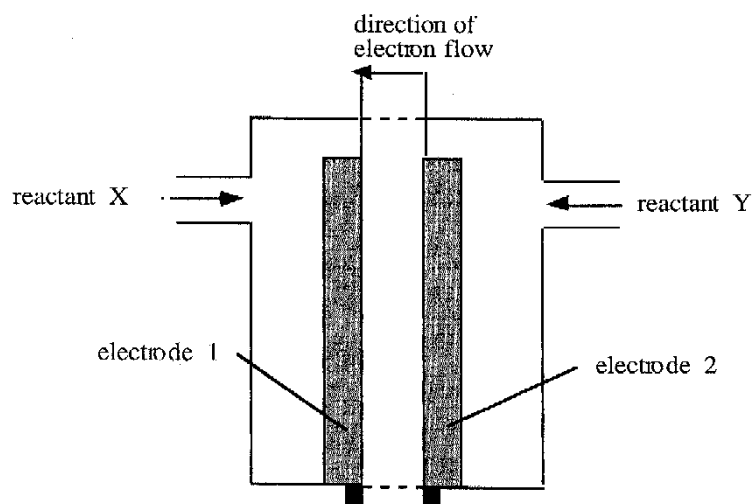
- (a) (i) Write the half-equation for the reaction at the cathode.
- (ii) Write the overall cell reaction.
- (b) On the diagram above, draw an arrow to indicate the direction in which the negative ion, X^- , moves.
- (c) State one advantage to the consumer of using fuel cells rather than other galvanic cells to produce energy.
- (d) What are the functions of the electrodes in the fuel cell?
- (e) Why are the electrodes porous?

(f) Suppose that a current drawn by a device connected to this fuel cell averages 5.00 A. What volume of hydrogen at STP is consumed by the cell each day if 70% of the energy produced by the cell is converted into useable electricity?

(g) If the electrolyte in this fuel cell was replaced with KOH , what differences would occur in the reactions occurring in the cell. State the corresponding half equations and overall equation.

QUESTION 39

Fuel cells are electrochemical cells that convert chemical energy into electrical energy. The diagram below shows an alkaline hydrogen–oxygen fuel cell.



- State the polarity of electrodes 1 and 2.
- State the reactants X and Y.
- State the reactions that occur at each electrode.
- Describe the changes in the pH of the solution close to each electrode when current is flowing. Explain your answer.

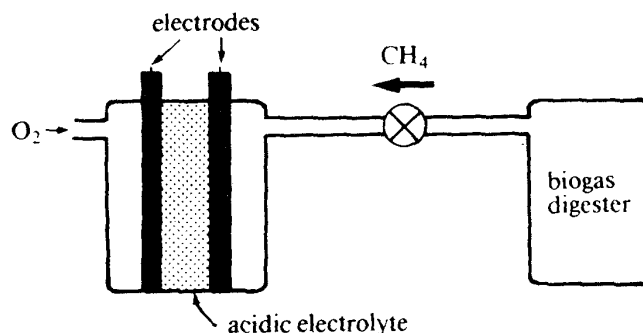
(e) This fuel cell operates at 80.0% efficiency, generating a current of 2.50 A and consuming 10.00 g of fuel in the process.

(i) For how long was the cell operating?

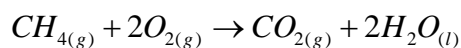
(ii) If the cell voltage is 1.20 V, what is the energy output of the cell per gram of fuel?

QUESTION 40

It has been suggested that in the future, some houses could obtain their electricity from a fuel cell which consumes methane and oxygen and uses an acidic electrolyte. A possible arrangement is shown below.



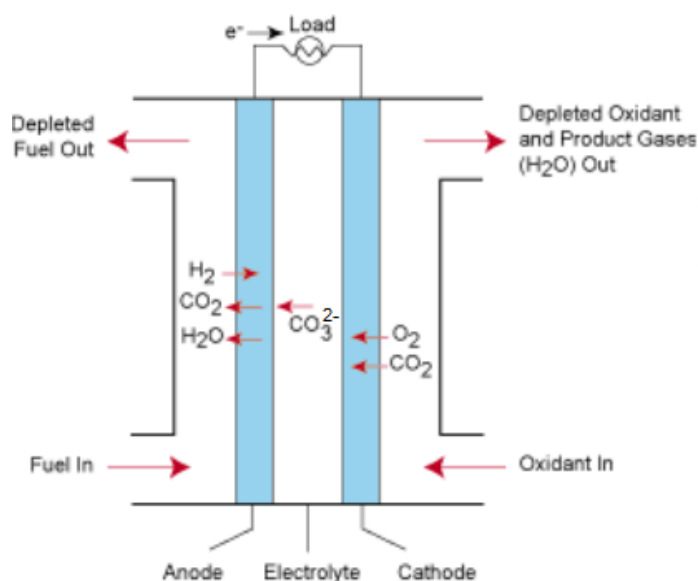
The overall equation for the reaction occurring in the fuel cell is:



- (a) What compound is oxidised in the reaction?
- (b) Write a partial ionic equation for the oxidation reaction.
- (c) What is the major difference between the operation of a fuel cell and the operation of galvanic cells such as the Dry Cell?
- (d) Suppose the current drawn by a household connected to this fuel cell averages 5.00 amp. What volume of methane at STP is consumed by the cell each day if 70% of the energy produced by the cell is converted into usable electricity?

QUESTION 41

Molten carbonate fuel cells (MCFCs) use a molten carbonate salt suspended in a porous ceramic matrix as the electrolyte. Salts commonly used include lithium carbonate, potassium carbonate and sodium carbonate.



- (a) When methane is used in the fuel cell, it is first reformed using steam to produce hydrogen gas and carbon monoxide. Write a balance equation for the reformation step.
- (b) The hydrogen produced in the reforming process is then used in the fuel cell. Determine the half equations and overall equation for the fuel cell.

- (c) Molten carbonate fuel cells operate at high temperatures. Give a reason for this.
- (d) What are the disadvantages of the high operating temperatures?
- (e) Molten carbonate fuel cells do not need expensive platinum catalysts. Suggest a reason for this.
- (f) Molten carbonate fuel cells can reach efficiencies approaching 60%, considerably higher than the 37–42% efficiencies of a phosphoric acid fuel cell plant. How could the efficiency be further improved?
- (g) Hydrogen gas can be sourced in a number of ways. How could the hydrogen used in this cell be sourced in order to have low environmental impact?

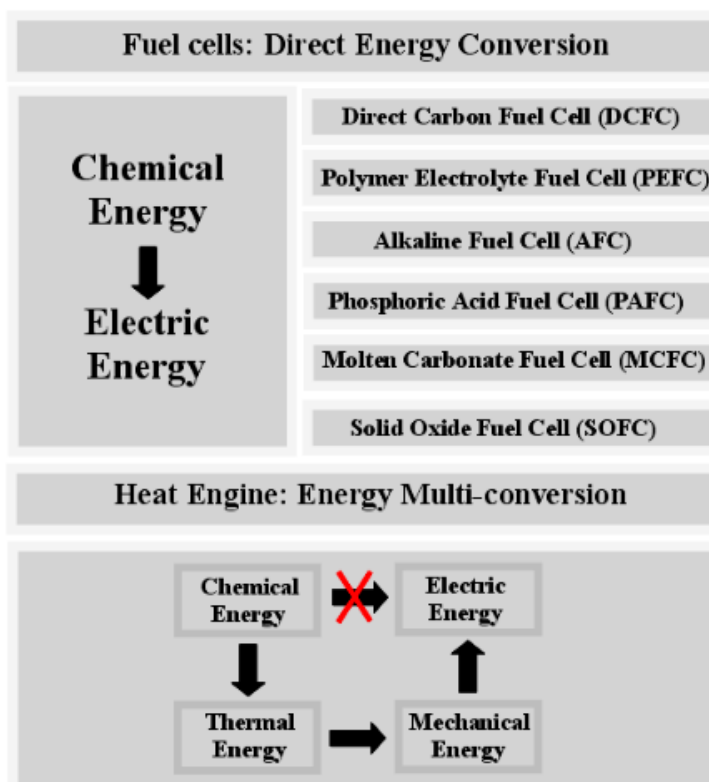
COMPARISON OF FUEL CELLS AND COMBUSTION OF FUELS

ENERGY EFFICIENCY

| | Energy Efficiency |
|-----------------------------|-------------------------|
| Fuel Cell | Ranges between 40 – 60% |
| Fuel Cell (CHP) | 80 – 90% |
| Internal Combustion engines | 25 – 30% |
| Thermal Power stations | 30 – 40% |

Fuel cells are more efficient than other energy sources since chemical energy is directly converted into electrical energy.

When electricity produced from fossil fuels, the chemical energy of the fuel undergoes many more energy transformations. This reduces efficiency due to the energy losses associated with each step.



Note:

- When the waste heat generated by fuel cells is captured in Combined Heat Power (CHP) systems, then the overall efficiency increases significantly.

SAFETY

The safety of a fuel depends on a number of factors including:

- Its volatility.
- Its ignition point.
- Its flash point.
- Its rate of dispersion when split.
- Ease of storage and transport.
- Visibility of flame.

One of the most common types of fuel cell is the hydrogen - oxygen fuel cell, so safety issues tend to focus on the safety of hydrogen compared to other fuels.

Characteristics of hydrogen:

- Odourless, colourless and tasteless which makes hydrogen leaks difficult to detect. Odorants are not effective with hydrogen since they disperse more slowly than hydrogen and hence do not enable the location of the hydrogen to be 'smelt'.
- Disperses rapidly. This can be good or bad. In an open space it means that hydrogen leaks will dissipate rapidly. However, in a confined space, the concentration of hydrogen can quickly build to dangerous levels. Hydrogen is about 57 times lighter than petrol.

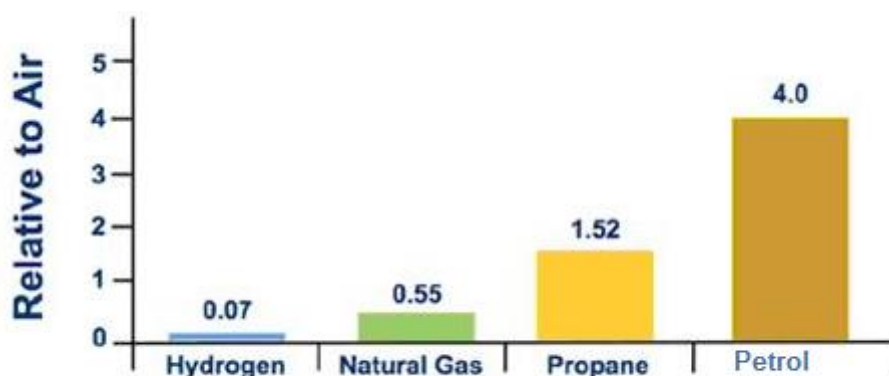


Figure 1. Relative Vapor Density

- Hydrogen has a low energy density per volume which makes it difficult to store efficiently. To minimise space, the hydrogen is compressed and stored at high pressure which involves the use of specialised, high pressure tanks. These tanks are generally fitted with relief valves which vent the hydrogen if the pressure is too high. This lowers the risk of the tanks exploding from excess pressure.
- The auto-ignition temperature of hydrogen is higher than many other combustible fuels. This is an advantage since it means it can reach higher temperatures before it spontaneously combusts.

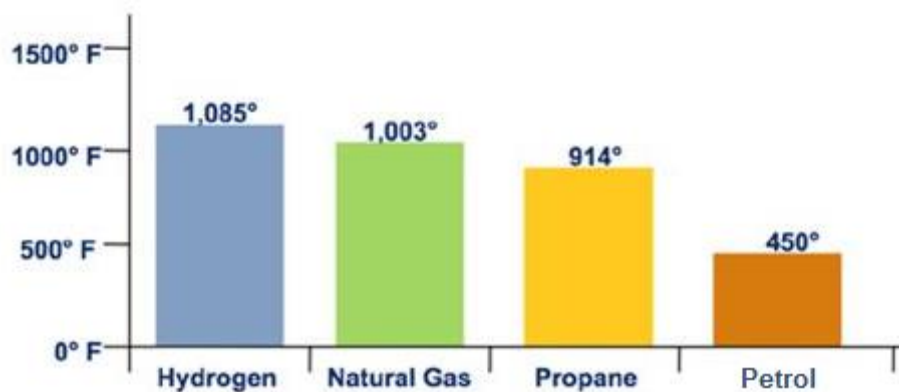


Figure 2. Auto Ignition Temperature

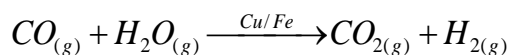
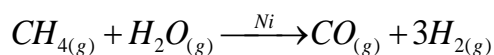
- Hydrogen burns with a blue flame which makes it difficult to see, particularly in daylight. Other fuels, such as propane, burn with yellow flames which makes them much easier to detect.
- Hydrogen emits very little infra-red light when combusted. This means that little radiant heat is felt even close to the flame. Incidental burns are therefore more common.
- Hydrogen burns quickly. This can cause a lot of steam to be produced in a small area and a short time frame. The thermal energy of steam can cause severe burns.
- Liquid hydrogen is stored at -253°C which can cause severe cold burns.
- Liquid hydrogen expands rapidly to 850 times its original volume when warmed to room temperature. This explosive expansion can be extremely dangerous if not controlled properly.

FUEL SUPPLY AND STORAGE

Producing Hydrogen

- Even though hydrogen is the most abundant element in the universe, it is not readily available in its pure form on Earth.
- Hydrogen can be produced from the electrolysis of water. Unfortunately this is an energy intensive process and involves the consumption of large amounts of electricity. If the electricity is produced via the combustion of fossil fuels, then emissions become a significant environmental problem. One solution is to generate the required electricity using renewable and carbon neutral fuels.
- Hydrogen can also be sourced from the reforming of hydrocarbons. When methane gas is reacted with steam in the presence of a catalyst, it forms hydrogen gas. This process also emits greenhouse gasses and other pollutants, but less than is produced via combustion. Reformers can be built into fuel cells so that fuels such as methane and methanol can be converted to hydrogen as needed.

Typical gas reforming reactions:



Storing Hydrogen

Hydrogen can be stored as:

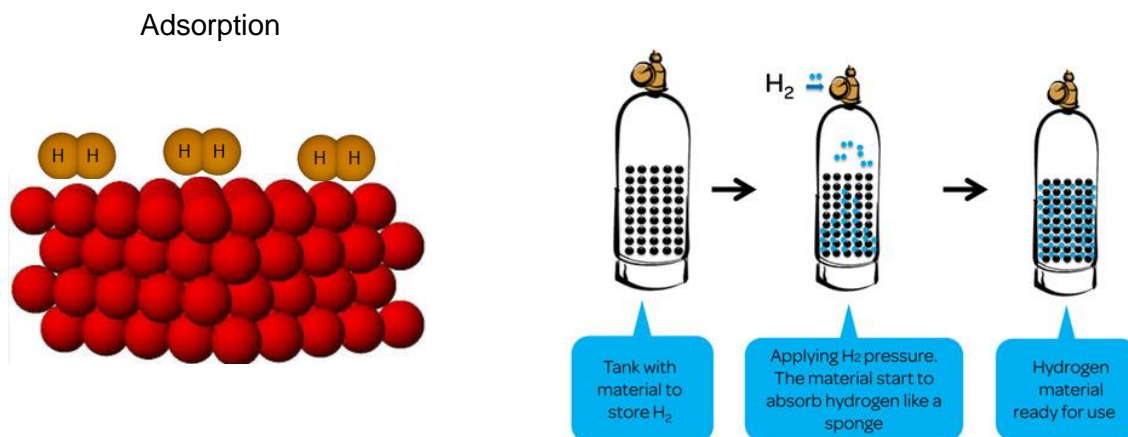
- Compressed hydrogen gas

This requires specialised tanks that can withstand high pressures. Even when compressed, the amount of storage space is still considerable.

- Liquefied hydrogen gas
 - Must be cryogenically stored at very low temperatures to keep it in the liquid state which is expensive.
 - Potentially very dangerous if warmed since the hydrogen changes state very rapidly resulting in a huge increase in volume.
 - Liquefied hydrogen has an energy density of 8 MJ L^{-1} which is approximately four times less than other hydrocarbon fuels like petrol 32 MJ L^{-1} .

- Adsorbed hydrogen gas

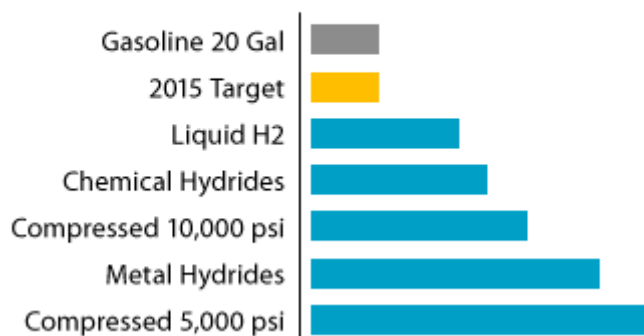
Storing hydrogen via adsorption onto metal hydrides or absorption into lattice structures may be a solution to the hydrogen storage problem.



- Stored as a component of a hydrocarbon or other organic fuel.

The hydrogen is stored as a component of another fuel such as an alcohol or hydrocarbon. These substances are then converted to hydrogen just before use via reformation. This process would emit some pollution but less than that produced by a combustion engine.

Relative Volume Needed for Hydrogen Storage to Achieve > 300 Mile Range



Comparison to other combustible fuels.

Using and storing hydrogen poses some unique challenges. Liquid fuels like ethanol, petrol and diesel are less volatile and easier to store and transport. Solid fuels, like coal are also significantly safer and easier to manage.

GREENHOUSE GASES

Fuel cells which run on hydrogen produce water, heat and small amounts of other emissions. Since the water produced is a liquid, there are essentially no greenhouse gases produced.

Fuel cells which run on other fuels such as methane, glucose or ethanol will produce comparable amounts of carbon dioxide as the combustion of those fuels since the overall reactions occurring are essentially the same.

APPLICATIONS

Portable power generation:

Small fuel cells can be used to directly power appliances or to recharge batteries. They can be used as a power supply in remote locations (e.g. when camping) or as a back up power supply when normal power distribution is offline.

Stationary power generation:

Fuel cells are capable of producing huge amounts of power and hence can be used as a primary power source rather than using the electricity grid. Fuel cells generate power 'on-site' which reduces the power loss associated with the transmission lines in traditional power supplies.

Transport power:

Fuel cells can be used in transport vehicles instead of traditional combustion engines.

Comparison of Fuel Cell Technologies

| Fuel Cell Type | Common Electrolyte | Operating Temperature | Typical Stack Size | Efficiency | Applications | Advantages | Disadvantages |
|---|---|--|------------------------------|--------------------------------------|---|--|--|
| Polymer Electrolyte Membrane (PEM) | Perfluoro sulfonic acid | 50-100°C 122-212° typically 80°C | < 1kW-100kW | 60% transportation 35% stationary | <ul style="list-style-type: none"> Backup power Portable power Distributed generation Transporation Specialty vehicles | <ul style="list-style-type: none"> Solid electrolyte reduces corrosion & electrolyte management problems Low temperature Quick start-up | <ul style="list-style-type: none"> Expensive catalysts Sensitive to fuel impurities Low temperature waste heat |
| Alkaline (AFC) | Aqueous solution of potassium hydroxide soaked in a matrix | 90-100°C 194-212°F | 10-100 kW | 60% | <ul style="list-style-type: none"> Military Space | <ul style="list-style-type: none"> Cathode reaction faster in alkaline electrolyte, leads to high performance Low cost components | <ul style="list-style-type: none"> Sensitive to CO₂ in fuel and air Electrolyte management |
| Phosphoric Acid (PAFC) | Phosphoric acid soaked in a matrix | 150-200°C 302-392°F | 400 kW 100 kW module | 40% | <ul style="list-style-type: none"> Distributed generation | <ul style="list-style-type: none"> Higher temperature enables CHP Increased tolerance to fuel impurities | <ul style="list-style-type: none"> Pt catalyst Long start up time Low current and power |
| Molten Carbonate (MCFC) | Solution of lithium, sodium, and/ or potassium carbonates, soaked in a matrix | 600-700°C 1112-1292°F | 300 kW-3 MW 300 kW module | 45-50% | <ul style="list-style-type: none"> Electric utility Distributed generation | <ul style="list-style-type: none"> High efficiency Fuel flexibility Can use a variety of catalysts Suitable for CHP | <ul style="list-style-type: none"> High temperature corrosion and breakdown of cell components Long start up time Low power density |
| Solid Oxide (SOFC) | Yttria stabilized zirconia | 700-1000°C 1202-1832°F | 1 kW-2 MW | 60% | <ul style="list-style-type: none"> Auxiliary power Electric utility Distributed generation | <ul style="list-style-type: none"> High efficiency Fuel flexibility Can use a variety of catalysts Solid electrolyte Suitable for CHP & CHHP Hybrid/GT cycle | <ul style="list-style-type: none"> High temperature corrosion and breakdown of cell components High temperature operation requires long start up time and limits |

PROBLEMS ASSOCIATED WITH HYDROGEN USE

The extensive use of fuel cells is being hampered by their start up and operating costs, the lack of infrastructure, the cost of producing hydrogen, and the difficulty of storing hydrogen.

Currently there is little infrastructure to support fuel cells, particularly those used in transport vehicles. Petrol stations are not currently equipped to store or deliver hydrogen in a safe and efficient manner.

Many fuel cells require the use of expensive metal catalysts such as platinum.

There are also costs associated with producing the fuels for example, the cost of producing the electricity for the electrolysis of water.

The auxillary systems used in the fuel cell also add cost. Pumps, reformers (e.g. conversion of methane/alcohol into hydrogen), waste removal and maintaining operating temperatures all add to the running cost.

Traditional fossil fuel based energy supply is still our major source of electrical power and transport energy. Fuel cells have not been able to compete with the ease and magnitude of fossil fuel supply.