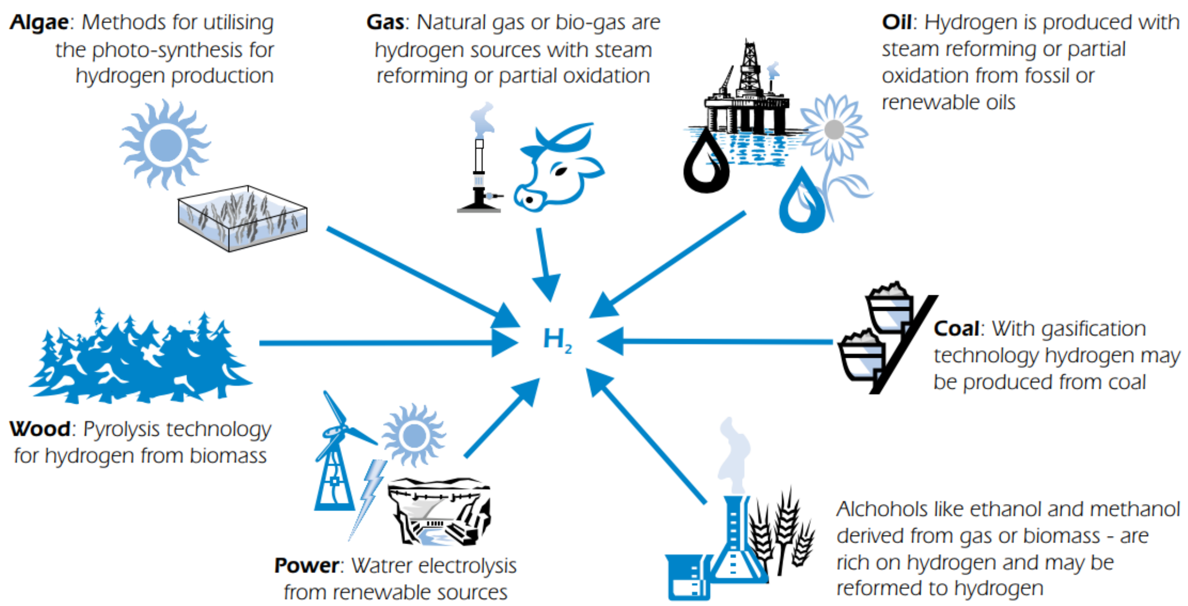
FUEL CELL TEST

INTRODUCTION

1. Hydrogen Production

Hydrogen can be produced from a variety of feed-stocks. These include fossil resources, such as natural gas and coal, as well as renewable resources, such as biomass and water with input from renewable energy sources (e.g. sunlight, wind, wave or hydro-power). A variety of process technologies can be used, including chemical, biological, electrolytic, photolytic and thermo-chemical. Each technology is in a different stage of development, and each offers unique opportunities, benefits and challenges. Local availability of feedstock, the maturity of the technology, market applications and demand, policy issues, and costs will all influence the choice and timing of the various options for hydrogen production. An overview of the various feed-stocks and process technologies is presented below:

Some feedstock and process alternatives



Algae: Methods for utilising the photo-synthesis for hydrogen production

Gas: Natural gas or bio-gas are hydrogen sources with steam reforming or partial oxidation

Oil: Hydrogen is produced with steam reforming or partial oxidation from fossil or renewable oils

Wood: Pyrolysis technology for hydrogen from biomass

Coal: With gasification technology hydrogen may be produced from coal

Power: Watrer electrolysis from renewable sources

Alchohols like ethanol and methanol derived from gas or biomass - are rich on hydrogen and may be reformed to hydrogen

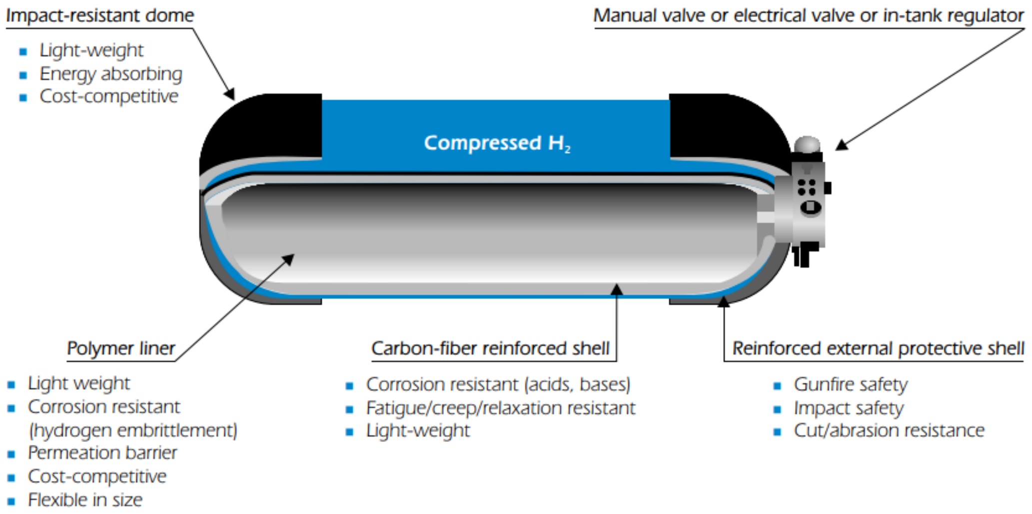
2. Hydrogen Storage

2.1. Gaseous Hydrogen

The most common method to store hydrogen in gaseous form is in steel tanks, although lightweight composite tanks designed to endure higher pressures are also becoming more and more common.

2.1.1. Composite tanks

- A schematic of a typical high-pressure, C-fibre-wrapped H_2 storage composite tank is shown below:



- High pressure range (350-700 bar)
- Research on material embrittlement.
- Development of stronger and lower-cost construction materials
- Development of techniques that recover the compression energy during vehicle operation

2.1.2. Glass microsphere

- The main problem with glass microspheres is the inherently low volumetric density that can be achieved and the high pressure required for filling.
- The glass microspheres slowly leak hydrogen at ambient temperatures.
- Development of stronger glasses.
- Development of specific low-cost production techniques.
- Development of coating techniques for optimization of H2 permeability.

2.2. Liquid Hydrogen

Cryogenic liquid hydrogen (LH2)

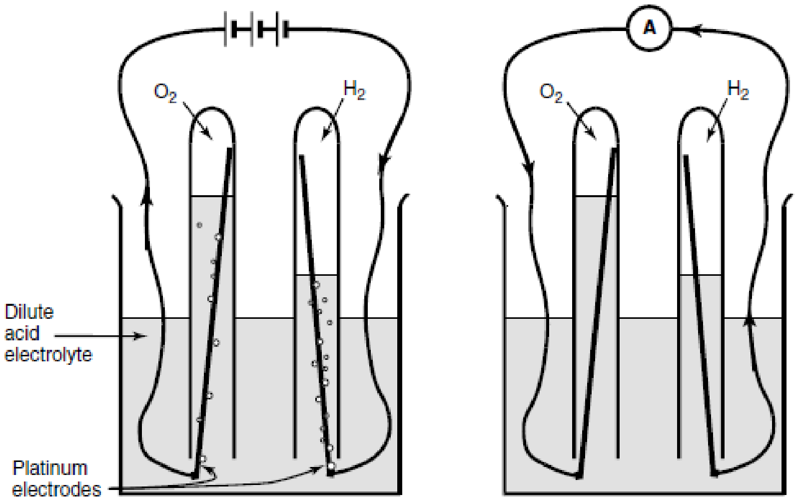
- Cryogenic hydrogen, usually simply referred to as liquid hydrogen (LH_2), has a density of 70.8 kg/m^3 at normal boiling point (–253 °C).
- Develop more efficient liquefaction processes.
- Lower costs and improve the insulated containers.
- Develop systems that automatically capture the **boil-off** and **re-liquefy** the fuel.

2.3. “Solid Hydrogen

- Storage of hydrogen in solid materials has the potential to become a safe and efficient way to store energy, both for stationary and mobile applications.
- Lower volume, lower pressure (higher efficiency), more purity of hydrogen.

HYDROGEN FUEL CELLS – Basic Principles

The basic operation of the hydrogen fuel cell is extremely simple. The first demonstration of a fuel cell was by lawyer and scientist William Grove in 1839, using an experiment along the lines of that shown in Figures 1.1a and 1.1b. In Figure 1.1a, water is being electrolyzed into hydrogen and oxygen by passing an electric current through it. In Figure 1.1b, the power supply has been replaced with an ammeter, and a small current is flowing. The electrolysis is being reversed – the hydrogen and oxygen are recombining, and an electric current is being produced. Another way of looking at the fuel cell is to say that the hydrogen fuel is being 'burnt' or combusted in the simple reaction.



(a) (b)

Note that the arrows represent the flow of negative electrons from – to +.

Figure 1.1 (a) The electrolysis of water. The water is separated into hydrogen and oxygen by the passage of an electric current. (b) A small current flows. The oxygen and hydrogen are recombining.

$$\mathbf{2H_2 + O_2 \rightarrow 2H_2O}$$

However, instead of heat energy being liberated, electrical energy is produced. The main reasons for the small current are;

- the low 'contact area' between the gas, the electrode, and the electrolyte – basically just a small ring where the electrode emerges from the electrolyte.
- the large distance between the electrodes – the electrolyte resists the flow of electric current.

To overcome these problems, the electrodes are usually made flat, with a thin layer of electrolyte. The structure of the electrode is porous so that both the electrolyte from one side and the gas from the other can penetrate it. This is to give the maximum possible contact between the electrode, the electrolyte, and the gas.

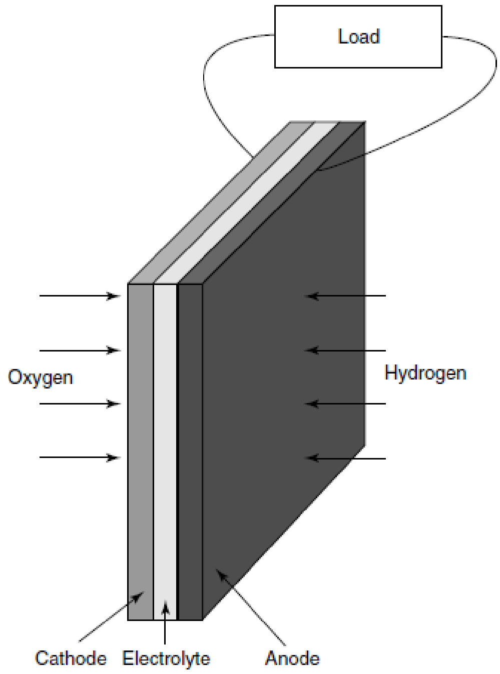


Figure 1.2 Basic cathode–electrolyte–anode construction of a fuel cell.

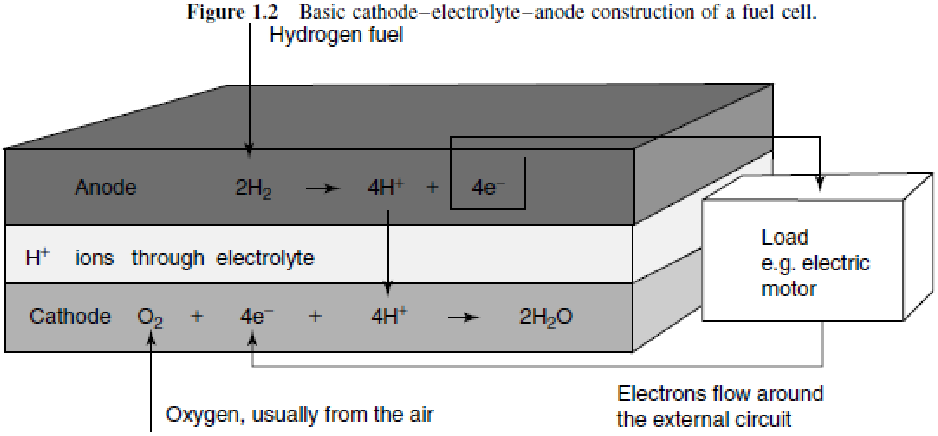


Figure 1.3 Electrode reactions and charge flow for an acid electrolyte fuel cell. Note that although the negative electrons flow from anode to cathode, the 'conventional current' flows from cathode to anode.

At the anode, hydrogen reacts, releasing energy. However, just because energy is released, it does not mean that the reaction proceeds at an unlimited rate. The reaction has the 'classical' energy. Although energy is released, the 'activation energy' must be supplied to get over the 'energy hill'. If the probability of a molecule having enough energy is low, then the reaction will only proceed slowly. Except at very high temperatures, this is indeed the case for fuel cell reactions.

The three main ways of dealing with the slow reaction rates are

- the use of catalysts,

- raising the temperature,
- increasing the electrode area

The electrode is made highly porous. This has the effect of greatly increasing the effective surface area.

1. Connecting Cells in Series – the Bipolar Plate

To connect several cells in series, anode/electrolyte/cathode assemblies need to be prepared. These are then ‘stacked’ together.

→ If the electrical contact is to be optimized, the contact points should be as large as possible, but this would mitigate the good gas flow over the electrodes.

→ If the contact points have to be small, at least they should be frequent. However, this makes the plate more complex, difficult, and expensive to manufacture, as well as fragile.

→ Ideally the bipolar plate should be as thin as possible, to minimize electrical resistance and to make the fuel cells stack small. However, this makes the channels for the gas flow narrow, which means it is more difficult to pump the gas round the cell.

2. Gas Supply and Cooling

→ Because the electrodes must be porous (to allow the gas in), they would allow the gas to leak out of their edges. The result is that the edges of the electrodes must be sealed.

→ ‘**External manifolding**’ has the advantage of simplicity. However, it has two major disadvantages (Figure 1.4).

The first is that it is difficult to cool the system. Fuel cells are far from 100% efficient, and considerable quantities of heat energy as well as electrical power are generated.

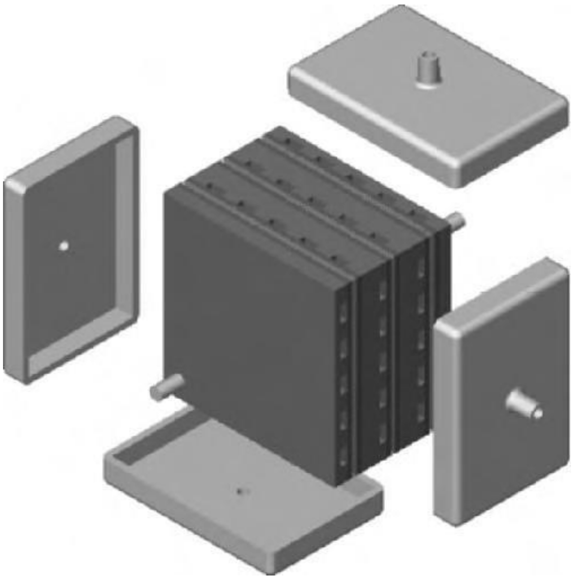


Figure 1.4. External manifolding

A more common arrangement requires a more complex bipolar plate. The plates are made larger relative to the electrodes and have extra channels running through the stack that feed the fuel and oxygen to the electrodes. Carefully placed holes feed the reactants into the channels that run over the surface of the electrodes. This type of arrangement is called ‘**internal manifolding**’ (Figure 1.5).

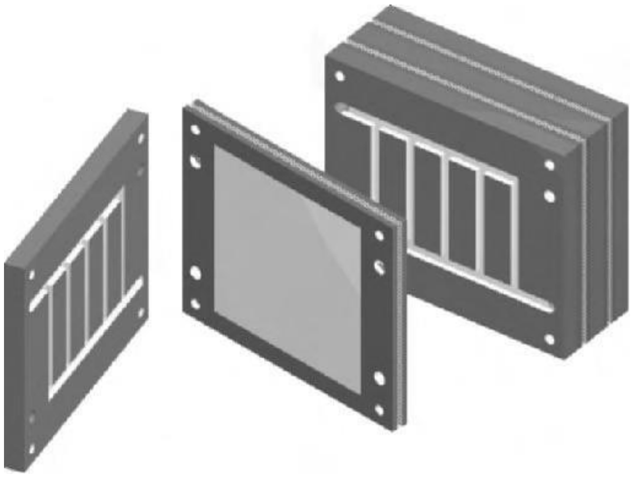


Figure 1.5. Internal manifolding

It should now be clear that the bipolar plate is usually quite a complex item in a fuel cell stack. In addition to being a fairly complex item to make, the question of its material is often difficult. **Graphite**, for example, is often used, but this is difficult to work with and is brittle. **Stainless steel** can also be used, but this will corrode in some types of fuel cells. **Ceramic** materials have been used in the very high temperature fuel cells. The bipolar plate nearly always makes a major contribution to the cost of a fuel cell. Anyone who has made fuel cells knows that leaks are a major problem. If the path of hydrogen through a stack using internal manifolding is imagined, the possibilities for the gas to escape are many. The gas must reach the edge of every porous electrode – so the entire edge of every electrode is a possible escape route, both under and over the edge gasket. Other likely trouble spots are the joints between each and every bipolar plate. In addition, if there is the smallest hole in any of the electrolytes, a serious leak is certain.

3. Fuel Cell Types

Leaving aside practical issues such as manufacturing and materials costs, the two fundamental technical problems with fuel cells are;

- the slow reaction rate, leading to low currents and power, and
- hydrogen is not a readily available fuel.

3.1. **The Proton Exchange Membrane Fuel Cell (PEMFC)** capitalizes on the essential simplicity of the fuel cell. The electrolyte is a solid polymer in which protons are mobile. The chemistry is the same as the acid electrolyte fuel cell of Figure 1.3. With a solid and immobile electrolyte, this type of cell is inherently very simple. These cells run at quite low temperatures, so the problem of slow reaction rates is addressed by using sophisticated catalysts and electrodes. Platinum is the catalyst, but developments in recent years mean that only minute amounts are used, and the cost of the platinum is a small part of the total price of a PEM fuel cell. The problem of hydrogen supply is not really addressed – quite pure hydrogen must be used, though various ways of supplying this are possible (Figure 1.6).

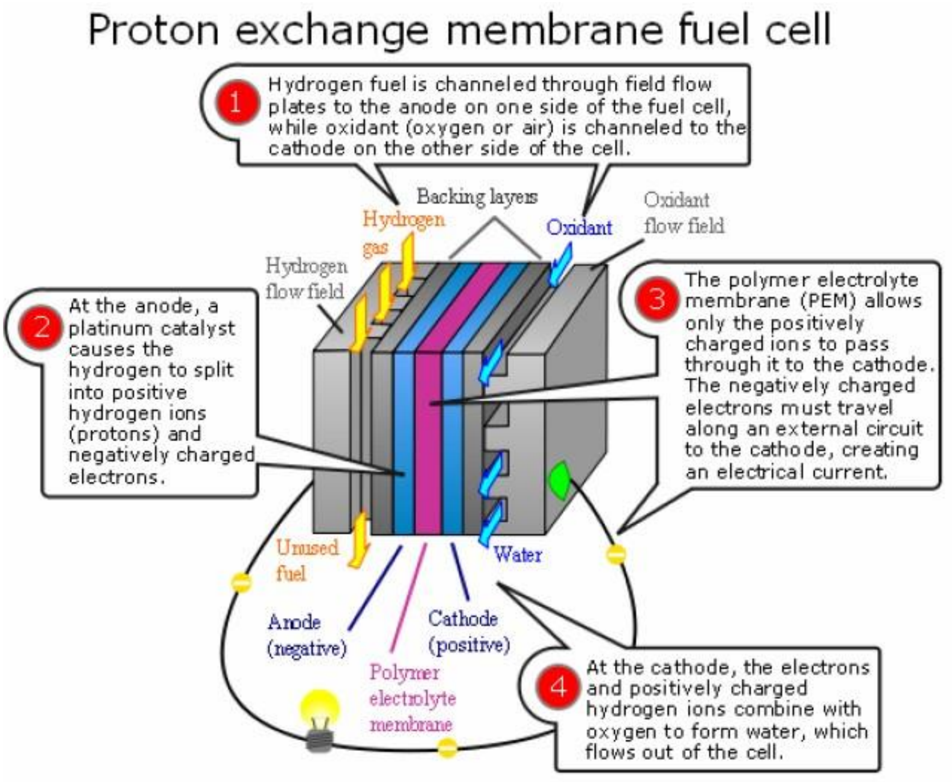


Figure 1.6. PEM Fuel Cell schematic

3.2. **Direct Methanol Fuel Cells (DMFC)** use the methanol as the fuel, as it is in liquid form, as opposed to extracting the hydrogen from the methanol.

- These cells have very low powers, but nevertheless, even at low power, there are many potential applications in the rapidly growing area of portable electronics equipment. Such cells, in the foreseeable future at least, are going to be of very low power, and used in applications requiring slow and steady consumption of electricity over long periods
- Their main problem is that the air and fuel supplies must be free from CO2, or else pure oxygen and hydrogen must be used.

3.3. **The Phosphoric Acid Fuel Cell (PAFC)** was the first to be produced in commercial quantities and enjoys widespread terrestrial use.

- The problem of fuelling with hydrogen is solved by ‘reforming’ natural gas (predominantly methane) to hydrogen and carbon dioxide, but the equipment needed to do this adds considerably to the cost, complexity, and size of the fuel cell system.

- Nevertheless, PAFC systems use the inherent simplicity of a fuel cell to provide an extraordinarily reliable and maintenance-free power system. Several PAFC systems have run continuously for periods of one year or more with little maintenance requiring shutdown or human intervention.

3.4. The Solid Oxide Fuel Cell (SOFC) operates in the region of 600 to 1000 ^{0}C. This means that high reaction rates can be achieved without expensive catalysts, and that gases such as natural gas can be used directly, or 'internally reformed' within the fuel cell, without the need for a separate unit.

- The high temperature means that a good reaction rate is achieved by using a comparatively inexpensive catalyst – nickel. The nickel also forms the electrical basis of the electrode.
- Like the SOFC it can use gases such as methane and coal gas (H2 and CO) directly, without an external reformer. However, this simplicity is somewhat offset by the nature of the electrolyte, a hot and corrosive mixture of lithium, potassium, and sodium carbonates. Table 1.1 demonstrates the summary of fuel cell types and application areas.

3.5. Molten carbonate fuel cell (MCFC) the interesting feature that it needs the carbon dioxide in the air to work.

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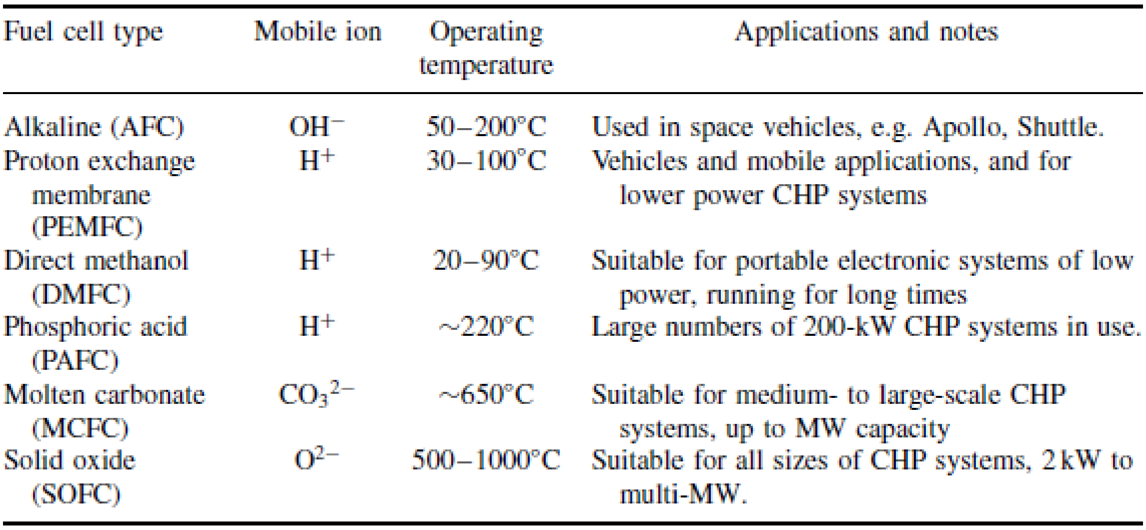
Table 1.1 Data for different types of fuel cell



Fuel cell type	Mobile ion	Operating temperature	Applications and notes
Alkaline (AFC)	OH^-	50–200°C	Used in space vehicles, e.g. Apollo, Shuttle.
Proton exchange membrane (PEMFC)	H^+	30–100°C	Vehicles and mobile applications, and for lower power CHP systems
Direct methanol (DMFC)	H^+	20–90°C	Suitable for portable electronic systems of low power, running for long times
Phosphoric acid (PAFC)	H^+	~220°C	Large numbers of 200-kW CHP systems in use.
Molten carbonate (MCFC)	CO_3^{2-}	~650°C	Suitable for medium- to large-scale CHP systems, up to MW capacity
Solid oxide (SOFC)	O^{2-}	500–1000°C	Suitable for all sizes of CHP systems, 2 kW to multi-MW.

4. Other Parts of a Fuel Cell System

- On all but the smallest fuel cells **the air** and **fuel** will need to be circulated through the stack using **pumps** or **blowers**. Often compressors will be used, which will sometimes be accompanied by the use of intercoolers, as in internal combustion engines.
- The direct current (DC) output of a fuel cell stack will rarely be suitable for direct connection to an electrical load, and so some kind of power conditioning is nearly always needed. This may be as simple as a voltage regulator, or a **DC/DC converter**. In combined heat and power (CHP) systems, a **DC to AC inverter** is needed, which is a significant part of the cost of the whole system. **Electric motors**, which drive the pumps, blowers, and compressors mentioned above, will nearly always be a vital part of a fuel cell system. Frequently also, the electrical power generated will be destined for an electric motor – for example, in motor vehicles.
- The supply and storage of hydrogen is a very critical problem for fuel cells. Fuel storage will clearly be a part of many systems. If the fuel cell does not use hydrogen, then some form of **fuel processing system** will be needed. These are often very large and complex, for example, when obtaining hydrogen from petrol in a car. In many cases desulphurization of the fuel will be necessary.
- Various **control valves**, as well as pressure regulators, will usually be needed. In most cases a controller will be needed to coordinate the parts of the system. A special problem the controller has to deal with is the start-up and shutdown of the fuel cell system, as this can be a complex process, especially for high-temperature cells.
- For all but the smallest fuel cells a **cooling system** will be needed. In the case of CHP systems, this will usually be called a **heat exchanger**, as the idea is not to lose the heat but to use it somewhere else. Sometimes, in the case of the higher-temperature cells, some of the heat generated in the fuel cell will be used in fuel and/or air pre-heaters. In the case of the PEM fuel cell, there is often the need to humidify one or both of the reactant gases.
- In the automotive industry, the two key figures are the **cost per kilowatt** and the **power density**. In round figures, current internal combustion engine technology is about 1kWL−1 and $10 per kW. Such a system should last about 4000 h (i.e. about 1 h use each day for over 10 years).

5. Advantages and Applications

The most important disadvantage of fuel cells at the present time is the same for all types – the **cost**. However, there are varied advantages, which feature more or less strongly for different types and lead to different applications.

- **Efficiency:** Fuel cells are generally more efficient than combustion engines whether piston or turbine based. A further feature of this is that small systems can be just as efficient as large ones. This is very important in the case of the small local power generating systems needed for combined heat and power systems.
- **Simplicity:** The essentials of a fuel cell are very simple, with few if any moving parts. This can lead to highly reliable and long-lasting systems.
- **Low emissions:** The by-product of the main fuel cell reaction, when hydrogen is the fuel, is pure water, which means a fuel cell can be essentially ‘zero emission’. This is their main advantage when used in vehicles, as there is a requirement to reduce vehicle emissions, and even eliminate them within cities. However, it

should be noted that, at present, emissions of CO2 are nearly always involved in the production of hydrogen that is needed as the fuel.

- **Silence:** Fuel cells are very quiet, even those with extensive extra fuel processing equipment. This is very important in both portable power applications and for local power generation in combined heat and power schemes.

EXPERIMENTATION

1. Determine the stack efficiency η_{stack} of this fuel cell by power balance.

$$\eta_{stack} = \frac{P_{out}}{P_{in}} = \frac{V_{stack}.I_{stack}}{LHV.\dot{V}_{H_2}}$$

Note: The lower heating value (LHV) of hydrogen at standard conditions is 10.8 MJ/m^3.

Measured Values			**Calculation**	
Fuel Consumption (l/min)	Current$_{stack}$(A)	Voltage$_{stack}$(V)	Power$_{stack}$(W)	η_{stack}

2. Plot the graphics of current versus efficiency and current versus power.