40 Using Galvanic Cells – Batteries

You have seen that galvanic cells generate an electrical potential difference from a spontaneous redox reaction and they can be represented as cell diagrams and anode and cathode half equations.

Galvanic cells are used as batteries. A battery is a source of electrical energy in which chemical energy is converted to electrical energy in one or more electrochemical (galvanic) cells. Batteries usually consist of a number of cells joined together.

A battery consists of a fuel (the material of the anode), an oxidant (the cathode material) and an electrolyte.

The anode is the electrode with the lower electrode potential – oxidation here releases electrons, thus producing an electric current.

Batteries are used extensively in portable devices such as mobile phones, radios, torches, calculators, smoke alarms, watches, cameras; in medical devices such as heart pacemakers and hearing aids; and as a way of storing electrical energy which has been produced by such sources as generators and solar cells.

Three common types of batteries are dry cell batteries, lead-acid batteries and lithium-ion batteries.

Dry cell batteries

Here we will look at two examples of dry cell (zinc/carbon) batteries – the Leclanche battery and alkaline batteries.

Alkaline batteries are similar to Leclanche batteries but contain a different electrolyte that allows them to supply a higher voltage for a longer period of time, thus increasing their usefulness.

The Leclanche battery. The dry cell is an inexpensive, battery that is durable and long-lasting but which cannot be recharged.

It consists of a zinc casing which acts as an anode, a central carbon rod which acts as a cathode and a paste of ammonium chloride and manganese dioxide which is the electrolyte.

The manganese ion is reduced and the zinc is oxidised producing a voltage of a little less than 1.5 volts.

$Zn(s) \rightarrow Zn^{2+}(aq) + 2e^-$

$Mn^{4+}(aq) + e^- \rightarrow Mn^{3+}$

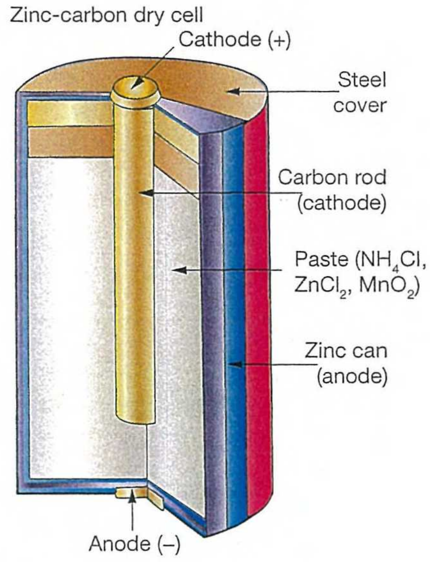


Figure 40.1 Internal structure of a dry cell.

Alkaline batteries. Alkaline batteries are a type of dry cell, which can supply a slightly higher voltage of 1.5 V and a current of 700 mA for a longer time than earlier dry cells. The electrolyte is a moist paste of potassium hydroxide or sodium hydroxide. Because alkaline cells deliver higher current and a greater total amount of electricity than Leclanche cells of a similar size, they are preferred in appliances that need a larger current such as cameras, hand tools and shavers.

Lead-acid batteries

This rechargeable type of battery is used in cars and consists of six cells combined in series to produce a bigger voltage (about 12 volts). In each cell, the electrodes consist of lead plates, which are the anodes, and plates coated in lead(IV) oxide which function as cathodes. These are immersed in the electrolyte, which is concentrated sulfuric acid solution (about 5 to 6 mol L^{-1}).

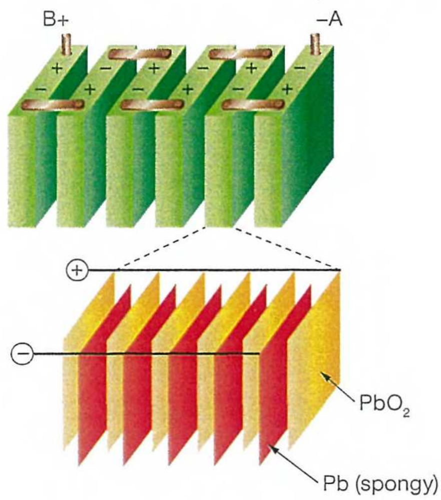


Figure 40.2 Lead-acid batteries.

Anode reaction: $Pb(s) \rightarrow Pb^{2+} + 2e^-$

Cathode reaction: $Pb^{4+}(aq) + 2e^- \rightarrow Pb^{2+}(s)$

The lead ions combine with sulfate ions to form insoluble lead(II) sulfate which accumulates on the electrodes. As the car motor runs, the car generator forces current back into the battery, the reactions are reversed and the battery becomes recharged.

Spent lead-acid batteries must be disposed of carefully because of the presence of concentrated acid and the toxic heavy metal lead.

Lithium-ion batteries

Lithium-ion batteries are the fastest growing type of rechargeable battery. They are long life, high energy, rechargeable batteries which generally produce from 1.5 to 3.7 volts. They are relatively expensive, but last longer than alkaline batteries and can be charged and discharged hundreds of times.

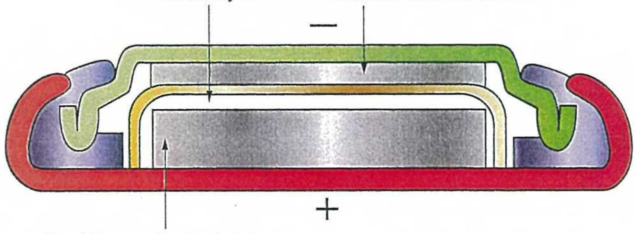


Figure 40.3 Lithium-ion battery.

There is a variety of lithium-ion batteries on the market, using different lithium compounds for the cathode, so the chemistry of these batteries varies. Generally the anode is made of carbon. Lithium ions are released at the anode, and travel to the cathode where they react. These reactions are reversed during recharging.

Lithium is an element with low density and it is highly reactive, giving lithium-ion batteries a high energy capacity. As lithium reacts with water, the electrolyte must be non-aqueous and the container must be well-sealed.

Batteries in hybrid vehicles

Hybrid vehicles are powered by an internal combustion engine and an electric engine that uses energy stored in a battery. The battery is charged by the internal combustion engine and also by using heat energy from braking that would normally be lost to the environment. The electric motor can be used as a generator and the captured energy is stored in the battery.

The battery can be used to help power the vehicle, provide extra power during acceleration and to power auxiliary features such as headlights and sound systems. The engine can shut off when the vehicle stops (such as at traffic lights), thus reducing the waste of fuel during engine idling. The vehicle can also be driven for short periods using only electric power. The use of a hybrid system can result in better fuel economy without reducing the performance of the vehicle.

The batteries used in hybrid vehicles can be nickel-metal hydride batteries or lithium-ion batteries. Nickel-metal hydride batteries have a longer life cycle than lead-acid batteries, however they are expensive, relatively heavy, generate heat at high temperatures and their hydrogen production must be controlled. Most of today's hybrid vehicles use lithium-ion batteries. These have a high power-to-weight ratio, high energy efficiency, good performance at high temperatures and also most components can be recycled.

A battery in a hybrid car may consist of 200 to 300 cells and produce a voltage of 200 to 500 volts.

Developments in batteries

Batteries are seen as useful technology in the search for clean energy. We need to replace fossil fuels and reduce carbon dioxide emissions. Energy produced by such sources as solar cells and wind power needs to be stored and released as needed. To do this we need better batteries and more of them.

Batteries are also needed to power the multitude of mobile electronic devices, such as cell phones, cameras and laptops, that many people now see as essential to maintain their preferred lifestyle.

Scientists are searching for materials that can be used to produce reliable energy sources – batteries that have more energy, weigh less, can charge rapidly, hold a charge longer and of course cost less.

Thanks to research, technological developments – which a few years ago were considered science fiction – are now being implemented and are seen around us. In Spain, a public lighting system for roads and parks has been introduced that uses a solar panel, a wind turbine and a battery.

Researchers are constantly working to make batteries more efficient and less expensive. New technology is increasing the speed (and decreasing the cost) of manufacturing components such as electrodes and electrolytes, and producing batteries which are more efficient, can last longer and be recharged more rapidly. Nanotechnology is playing a crucial role in many research projects.

41 Using Galvanic Cells – Fuel Cells

A **fuel cell** is a type of galvanic cell in that it converts the chemical energy from a fuel directly into electricity. It is very efficient as it has no moving parts. Fuels used in fuel cells can include hydrogen, and methanol.

Fuel cells are **different from batteries** in that batteries store the chemical energy to be used, whereas fuel cells need a continuous supply of fuel and air. Fuel cells can produce a continuous supply of electrical energy as long as there is a continuous supply of fuel and air.

Fuel cells work on the principle of exchanging electrical charge between an anode and a cathode. A redox reaction occurs between oxygen from the air and a fuel such as hydrogen. In a fuel cell, hydrogen can react with oxygen without the flames of a combustion reaction.

Composition of fuel cells

All fuel cells consist of:

- A negative anode – produces a flow of electrons as a fuel (e.g. hydrogen) is oxidised.
- A positive cathode – receives electrons and oxygen is reduced.
- An electrolyte – allows charges to move from one side of the fuel cell to the other. Fuel cells are usually classified according to the type of electrolyte used, e.g. there are alkaline, molten carbonate, phosphoric acid, solid oxide and proton exchange membrane fuel cells.
- An external circuit – electrons are drawn from the anode to the cathode through this external circuit.
- Fuel – the most common fuel is hydrogen. Hydrocarbons such as methanol can also be used.

When **hydrogen is used as the fuel**, the process is like the reverse of electrolysis. Chemical energy is converted to electricity, and the only by-products are water and heat.

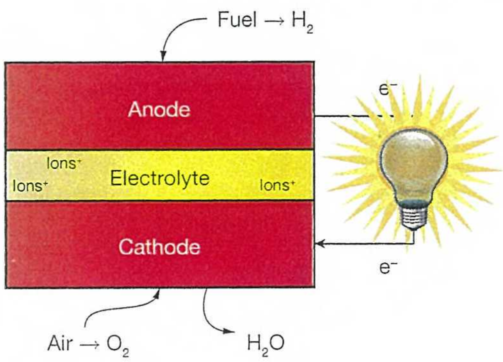


Figure 41.1 A simple fuel cell.

Other fuels such as methanol can be used. Methanol is more portable so it could be more convenient for use in cars, but its use, like that of petrol, produces carbon dioxide.

Proton exchange membrane fuel cell

The proton exchange membrane fuel cell (PEMFC) is a hydrogen fuel cell which uses membrane technology and is one of the most promising fuel cell technologies. The electrolyte in these cells is a polymer membrane which can conduct protons (hydrogen ions) but not electrons.

At the anode – The hydrogen fuel is broken down using a catalyst such as platinum – hydrogen is oxidised. Electrons are separated from the hydrogen atoms leaving protons – remember, a proton is a hydrogen ion.

The electrons travel out of the cell in a circuit – they produce the **flow of electricity**. The protons move through the **electrolyte** (polymer membrane) to the cathode.

At the cathode – Oxygen gas (O_2), in contact with a catalyst, splits into two oxygen atoms which then combine with the protons (hydrogen ions) and electrons to produce water. Oxygen is reduced.

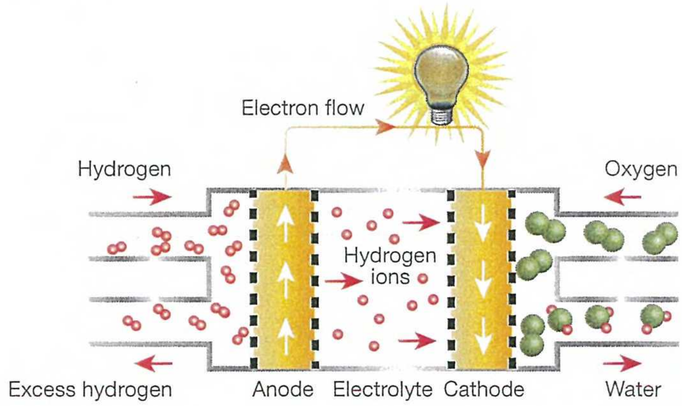


Figure 41.2 A proton exchange membrane fuel cell.

Catalysts are used in fuel cells, at the anode and the cathode, to improve the efficiency of the cell.

At the cathode, a catalyst such as nickel can be used to speed up the conversion of ions into waste chemicals such as water.

At the anode, very fine platinum powder is used as a catalyst to speed up the breakdown of fuel into ions and electrons. Platinum is a very effective catalyst, but it is rare and extremely expensive. Metal catalysts such as platinum can be used in the form of **nanoparticles** which can be added to multiwalled carbon nanotubes, or other types of carbon matrix.

Metal nanoparticles have a higher surface area than larger pieces of metal, allowing for an increased rate of reaction. The use of nanoparticles also allows for a reduction in the amount of metal needed for catalysis, which decreases production costs.

Research is ongoing to control the packing density of platinum nanoparticles as this affects their efficiency as a catalyst. Scientists are also working on the development of less expensive catalysts such as cobalt particles coated with graphene – transparent sheets of pure carbon only one atom thick.

Uses of fuel cells

Fuel cells were **invented in 1838**, but it took a century for them to become commercially useful. The NASA space program first developed fuel cells to provide power and water for **satellites and space capsules**.

Today there are many types of fuel cells being used and others under development. They can be used as both stationary and mobile sources of electricity.

Fuel cells can be used in **buildings**, as the primary source of electrical energy, or as a back-up source. As they do not produce the pollutants of traditional coal fired plants, they can be located on site. The heat produced during their operation can be used within the building. They are especially useful in remote areas.

Portable fuel cells can be used to power vehicles and may eventually replace the internal combustion engine which burns fossil fuels. Hydrogen fuel cells are being used in some vehicles, but research is still needed to develop ways of safely storing the hydrogen needed. Possibilities being investigated include using metal hydrides (weight problem), using carbon nanotubes, and using tanks of high pressure hydrogen (dangerous in a crash and takes up too much room).

Portable fuel cells are also being developed for use in such applications as mobile phones, computers, cameras and power tools. They also function as portable power generators for use in camping and emergency situations.

Efficiency of fuel cells

Fuel cells in motor vehicles are expected to achieve an efficiency of about 64%, which compares favourably with the 30% efficiency of the combustion engine. However, you need to also factor in that hydrogen does not occur – as an element – anywhere on Earth, so energy is needed to extract hydrogen from hydrogen compounds. Rapid advances in technology are being made and fuel cells may eventually be able to compete economically with other energy sources.

Fuel cells can operate continuously, as long as a fuel is supplied, because no permanent chemical change occurs to the cell.

QUESTIONS

1. (a) What is meant by a fuel cell?
   (b) List the five major components of a fuel cell.
   (c) Use a diagram to show the structure of a fuel cell.
2. Compare fuel cells to batteries.
3. Outline the use of catalysts in fuel cells.
4. Hydrogen is the most abundant element in the Universe as a whole, but it does not occur naturally on Earth. Investigate sources currently used to produce the hydrogen needed for use in hydrogen fuel cells.
5. Discuss any environmental impact resulting from the use of hydrogen fuel cells.
6. Outline the relevance of international cooperation, codes and standards to the use of fuel cells.
7. The International Partnership for Hydrogen and Fuel cells in the Economy (IPHE) is an organisation started as a United States initiative in 2003 with the aim of fostering a collaborative approach to fuel cell research and development. Australia is one of the 18 member countries. Continued energy supply to a growing world population is an important 21st century task. Discuss the importance of the role of an organisation such as the IPHE in overcoming problems with world energy supply
8. Check your knowledge with this quick quiz.
   (a) The electrodes in a fuel cell are called .... and ....
   (b) The anode in a fuel cell is (positively/negatively) charged.
   (c) Hydrogen gas used in a fuel cell as fuel, enters through the (anode/cathode).
   (d) Name two by-products produced by a hydrogen fuel cell.
   (e) These by-products are produced at the (anode/cathode).
   (f) Electrons are produced at the (anode/cathode).
   (g) In a hydrogen fuel cell, each hydrogen atom is split into a .... and ....
   (h) What is the electrolyte made of in a proton exchange membrane fuel cell?
   (i) This electrolyte must allow for the passage through it of .... but not ....
   (j) A catalyst in a fuel cell could be made of ....
   (k) A fuel cell converts .... energy into .... energy.
   (l) Name a chemical other than hydrogen that is used as a fuel in fuel cells.

48 Electrochemical Cells

Galvanic (voltaic) cells and electrolytic cells both involve electron transfer redox reactions, so they are both described as **electrochemical cells**.

You have seen that, although they both involve redox reactions, they work in different ways and have different uses. We can summarise the differences between galvanic and electrolytic cells as follows.

Table 48.1 Comparing galvanic and electrolytic cells.

Electrochemical cells	
Galvanic/voltaic cells	**Electrolytic cells**
Redox reactions occur that are **spontaneous**.	Redox reactions occur that are **not spontaneous**. A voltage is needed to force these reactions to take place.
$E^{\ominus}$ **value** for the redox reaction is positive.	$E^{\ominus}$ **value** for the redox reaction is negative.
A redox reaction produces an electric current.	An electric current produces a redox reaction.
Chemical energy is changed to electrical energy.	Electrical energy is changed to chemical energy.
The galvanic cell forms a battery. The **anode** is the negative terminal of this battery and the **cathode** is the positive terminal. The anode releases electrons, becomes positively charged, and can then attract negative ions present in the electrolyte.	The electrolytic cell uses electricity. The **anode** is the positive electrode. The **cathode** is the negative electrode.
Electrons flow through the wire connecting the negative terminal of the battery (the cell anode) to the positive terminal of the battery (the cell cathode).	**Electrons flow** from the negative terminal of the power source to the negative cathode and from the positive anode to the positive terminal of the power source.
Examples: batteries such as alkaline batteries and the lead-acid battery.	**Examples**: Electrolysis of water in a voltameter, electrolysis of brine in a membrane cell, electroplating, extracting metals from compounds.

Electrochemistry has a wide range of **uses**, from the production of batteries to personal cosmetic treatments and industrial processes that produce large volumes of chemicals such as metals and sodium hydroxide.

Research is ongoing, technology is improving as nanotechnology helps to make batteries smaller, improved membranes are developed for cells and new uses are being found for this technology.

One relatively new technology uses electrochemistry to purify mineral rich bore water. This was developed in New Zealand where the ground water contains high levels of iron and manganese derived from the surrounding rocks. It has applications in Australia as so many areas of our country rely on bore water as their main source of water.

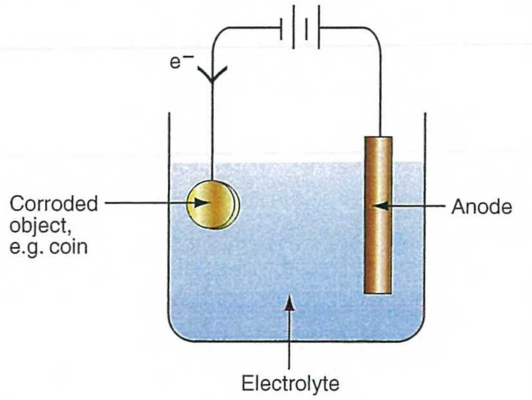
The high mineral content of bore water makes it undrinkable. Previously the water was treated with chemicals to precipitate out the minerals, and then filtered. This was expensive and difficult due to the presence of colloidal suspensions. The use of electricity to oxidise pollutants, making them easier to remove was initially expensive. But a new, more efficient cell has now been developed with porous electrodes that can be operated with lower voltage, even a 12 volt battery.

The electric current oxidises chloride ions to chlorine at the anode. The chlorine can then oxidise metals such as iron and manganese and at the same time it can disinfect the water.

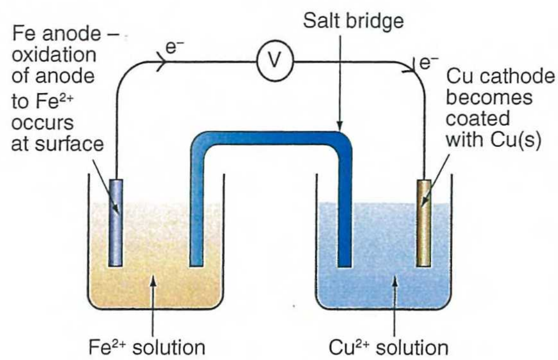
QUESTIONS

1. The electrochemical cells in the following diagrams involve redox reactions. Identify each cell as either galvanic or electrolytic. Justify your answers.

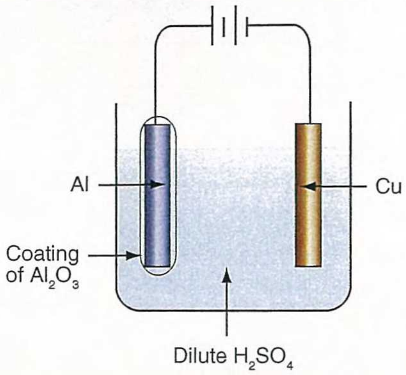
(a)



(b)

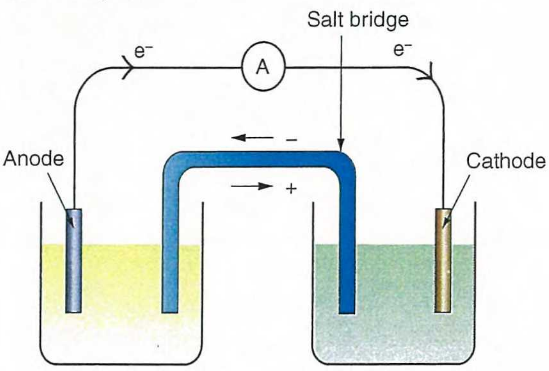


(c)

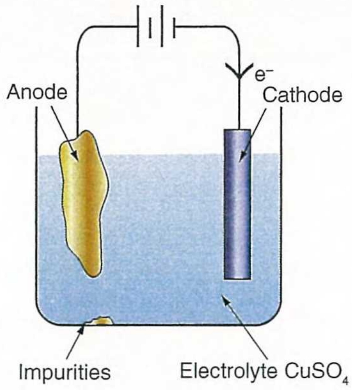


(d)

2. State whether a galvanic/voltaic cell or an electrolytic cell would be used for each of the following purposes.
   (a) Coating an ornament with silver.
   (b) Purifying copper.
   (c) Starting a car.
   (d) Galvanising iron.
   (e) Coating food cans with tin.
   (f) Extracting metals from compounds.
   (g) Making a torch work.
3. Outline three uses of electrolytic cells.
4. Compare galvanic and electrolytic cells in terms of spontaneity and the energy changes which occur.
5. In each of the following diagrams, circle any galvanic cell present.
   (a)



(b)



6. Research one aspect of electrochemical cells which interests you. Some examples of topics are listed below. Alternatively you could suggest another topic to your teacher.
   - Their use in hybrid cars.
   - The refining of metals.
   - The extraction of metals from ores.
   - The future of fuel cells.
   - Coating jewellery by electrolysis.
   - The history of electrolysis.
   - International collaboration on new developments.
   - Cutting edge technology.
   - Cells and pollution.
   - Economic aspects of using electrochemical cells.
   - What do industrial electrolytic cells look like?
   - What is electrowinning?
   - Is the use of electrochemical cells sustainable?
   - Electrochemical cells and safety issues.
7. Check your knowledge with this quick quiz.
   (a) Name two types of electrochemical cells.
   (b) Does a galvanic or an electrolytic cell require a power source in the external circuit?
   (c) Which type of electrochemical cell can produce electricity, a galvanic or an electrolytic cell?
   (d) Identify the electrode at which oxidation occurs in both galvanic and electrolytic cells.
   (e) Identify the reaction that occurs at the cathode in electrolytic and galvanic cells.
   (f) Which involves a spontaneous redox reaction, a galvanic or electrochemical cell?
   (g) Which type of cell converts chemical energy to electrical energy?

In older devices, the reduction reaction involved the change of dichromate ions to chromate ions. This was shown by a colour change from orange to green which was used to measure the alcohol concentration. The oxidation reaction was the same, but the reduction reaction was:

$Cr_2O_7^{2-} + 14H^+ + 6e^- \rightarrow 2Cr^{3+} + 7H_2O$

Orange green

(b) Various. In your answer you should include the following. Identify the effects of excessive alcohol on the body, e.g. slow reaction time, impaired judgement. Describe some situations in which alcohol consumption poses a risk, e.g. driving a vehicle, operating machinery, in the airline industry.
Explain how the introduction of random breath testing, carried out by the police, has improved the awareness and care taken by people driving vehicles. Technology has improved the accuracy and portability of devices so that it is now possible for individuals to test their own alcohol levels before attempting to drive. The accurate determination of blood alcohol levels is also important in legal matters where the likely degree of impairment needs to be established.
Conclude with an evaluation statement that *reflects your views – based on the information you have provided in your answer* – to what extent do *you* think that scientific knowledge helps us to monitor and manage the risk?

6. (a) Galvanic.
(b) Chemical, electrical.
(c) Various, e.g. alkaline batteries, lead-acid batteries, lithium-ion batteries.
(d) Various, e.g. watches, laptops, pacemakers, radios, mobile phones, cameras, hearing aids.

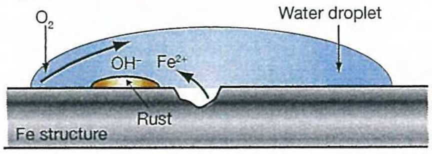
41 Using Galvanic Cells – Fuel Cells

1. (a) A fuel cell is a type of galvanic cell. It converts the chemical energy from a fuel directly into electricity using fuels such as hydrogen and methanol.
(b) Negative electrode (anode), positive electrode (cathode), electrolyte, external circuit, fuel.
(c) Various. A labelled diagram similar to Figure 41.1. or 41.2.
2. Fuel cells and batteries both convert the chemical energy stored in a fuel directly to electrical energy.
In a battery, the chemical energy is stored within the battery and the battery works until the fuel is used up. Some batteries can be recharged. In a fuel cell, the cell must be provided continuously with fuel and oxygen. It produces electricity as long as this fuel and oxygen are being supplied in a continuous stream.
3. Various. Catalysts are used to improve the efficiency of fuel cells. At the anode they help to increase the surface area for absorbing fuel and also for particles to react. At the cathode they increase the efficiency of absorbing oxygen and speed up the production of waste such as water. Nanotechnology has made it possible to produce more efficient catalysts.
4. Hydrogen exists on Earth in water and in most organic compounds. Most hydrogen is currently made by the action of steam on natural gas using a catalyst such as nickel – a process called steam reforming.
$CH_4(g) + 2H_2O(g) \rightleftharpoons CO_2(g) + 4H_2(g)$
Other methods of hydrogen production are being investigated, for example:
   - It can be obtained from water by electrolysis, but this is an expensive process unless it can be carried out using solar energy or other renewable energy sources.
   - Using photosynthetic microbes to use light in order to produce hydrogen as part of their metabolism.
   - Fermentation of renewable biomass.
   - Converting biomass from agricultural residues such as peanut shells.

5. The operation of a hydrogen fuel cell produces only water and heat as by-products. The heat can be captured and used, water is not polluting, as long as hot water is not disposed of into waterways to cause thermal pollution. So the operation of the fuel cell itself is non-polluting.
There are however some problems with the production and transport of hydrogen. Hydrogen is the most abundant element in the Universe, but it does not occur as a gas on Earth so it has to be produced, transported and stored.
Currently most hydrogen is currently made by the action of steam on natural gas using a catalyst such as nickel – a process called steam re-forming, which produces polluting carbon dioxide, a greenhouse gas. $CH_4(g) + 2H_2O(g) \rightleftharpoons CO_2(g) + 4H_2(g)$. Other methods are being investigated.
The transport and storage of hydrogen presents problems because it is a gas, making it easy to be released into the atmosphere, and it is also flammable, which is a safety concern.
An efficient system to produce, store, transport and use hydrogen gas would be expensive, and in reality some would escape to the atmosphere – some scientists estimate possibly as much as 10% to 20%. If hydrogen fuel cells replaced petrol engines, this would mean a lot of hydrogen being released into the atmosphere. Hydrogen is less dense than air, so it would rise in the atmosphere. In the stratosphere, it would be oxidised, producing a cooling effect which could increase cloud formation and affect movements of gases in the upper atmosphere. This could make the holes in the ozone layer become larger and last longer. Much more research is needed into possible effects of the release of hydrogen into the atmosphere and its ability to be absorbed, perhaps into soil.
Other potential environmental impacts could be caused by the production and disposal of the cell itself and of its catalysts, such as platinum or nickel. Research is underway to minimise any potential effects, for instance by the use of nanoparticles,
6. Problems are developing throughout the world associated with our production and uses of energy. Fossil fuels have been the predominant source of energy, but that needs to change because of limited resources, and the effects of the pollution resulting from their use – for example climate change. The move is towards the use of other technologies such as wind power, solar power and the use of hydrogen. This needs to be a global enterprise as climate change affects all countries and the need for fuel is worldwide.
As different countries strive to develop these new technologies there is concern that different regions and countries will develop different standards and codes of operation which will cause confusion, possibly safety issues, together with commercial trading problems. The fragmentation of codes and standards would be detrimental to the introduction of such new technologies. This is especially so for hydrogen fuel cells as they can theoretically be transported from country to country – but not unless they meet all codes and standards for each country and region.
Governments, scientists and businesses, from all regions and nations, need to communicate and cooperate to produce uniform standards and codes of operation for all phases of the development of new technologies such as fuel cells. This includes methods of production and transport for fuels such as hydrogen and methanol, as well as for the fuel cells themselves.
7. Fuel cells are likely to play an increasingly important role in energy production and use as the world moves away from its dependence on fossil fuels and towards renewable energy sources. However, there are currently problems to be overcome such as the supply and storage of fuel (e.g. hydrogen) and the efficiency, portability and safety of the cells.
Research and development costs are large. New technologies are often more expensive, when first introduced, than established technologies. Only by sharing the cost of research and development will the future use of fuel cells be accelerated.
The IPHE is an organisation which aims to coordinate global research, development and implementation of fuel cells in order to improve world energy supplies and help protect the environment. This organisation holds conferences and meetings to provide a forum for the sharing of ideas and information and to provide educational materials especially to governments. Such a collaborative approach will accelerate the use of fuel cells as an important part of our future energy economy.

[redacted]

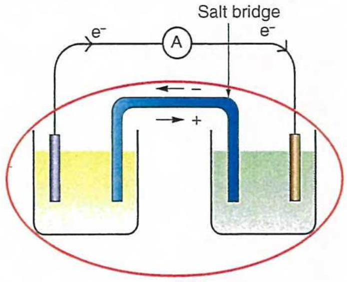
3. Various. Your answer should include arguments for and against sustainability, drawing from areas such as those listed below.
   - Uses of iron and its importance to society.
   - Our iron resources – how much longer will they last?
   - Environmental problems associated with mining, processing, and transporting the ore, coke and limestone as well as the chemical processing plant itself.
   - How any problems are being dealt with – are existing measures sufficient?
   - What else can we do, e.g. recycling.
   - Assessment – Is this process sustainable? Make a statement supported by the information you have presented.
4. An electrochemical process is one that is either caused or accompanied by the passage of an electric current – it involves electron transfer. Rusting is a redox reaction involving electron transfer, so it is electrochemical, as shown by the diagram and equations below.



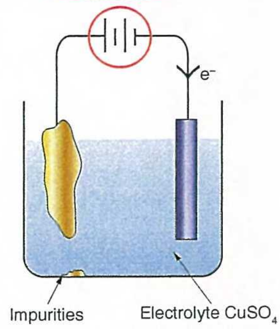
Anode reaction: $Fe(s) \rightarrow Fe^{2+}(aq) + 2e^-$ (Fe is oxidised).
Cathode reaction: $O_2(g) + 2H_2O + 4e^- \rightarrow 4OH^-$
Full reactions: $2Fe(s) + O_2(g) + 2H_2O(l) \rightarrow 2Fe^{2+}(aq) + 4OH^-(aq)$
$Fe^{2+}(aq)\ ) + 2OH^-(aq) \rightarrow Fe(OH)_2(s)$
The hydroxide is further oxidised to the hydrated iron(III) oxide that we call rust ($Fe_2O_3.xH_2O$) where x is usually 1 or 2.
The *overall equation* can then be written as:
$4Fe(s) + 3O_2(g) + 2H_2O(l) \rightarrow 2Fe_2O_3.H_2O(s)$
5. Iron has a lower reduction potential (−0.44 V) than copper (0.34). Electrons flow from the most negative area (iron) to the most positive area (copper). A galvanic cell occurs, with the copper coated part of the nail forming the cathode (so the nail is not oxidised), while the uncoated iron forms the anode and is corroded, forming hydroxide ions and turning the indicator dark blue.
6. (a) A sacrificial anode is a piece of metal which is attached to a less reactive metal in order to protect the less reactive metal from corrosion, e.g. magnesium or zinc attached to iron to prevent the iron corroding. The iron becomes the cathode of a galvanic cell while the active metal becomes the anode and is oxidised.
   (b) Magnesium or zinc.
7. (a) Tin is less reactive than steel (iron) so is less likely to react with the food and cause spoilage.
   (b) If the tin lining is damaged, such as when a tin becomes dented, then a galvanic cell will form and the steel will rust more rapidly than if the tin lining was not present.
8. (a) Carbon or carbon monoxide.
   (b) +3 to 0.
   (c) Reduced.
   (d) 0 to +2.
   (e) Reductant.
   (f) Galvanising.

48 Electrochemical Cells

1. (a) Electrolytic cell. This cell is being supplied with electricity to force a non-spontaneous redox reaction to occur.
   (b) Galvanic cell. This cell is producing electricity and the potential difference produced is being measured by means of a voltmeter. There is no external source of electrical energy. A spontaneous redox reaction is taking place.
   (c) Electrolytic cell. This cell is being supplied with electricity to force a non-spontaneous redox reaction to occur.
   (d) Galvanic cell. These are dry cell batteries, they produce electricity by means of a spontaneous redox reaction.
2. (a) Electrolytic cell. (b) Electrolytic cell.
   (c) Galvanic/voltaic cell. (d) Electrolytic cell.
   (e) Electrolytic cell. (f) Electrolytic cell.
   (g) Galvanic/voltaic cell.
3. Various. Three uses of electrolytic cells are:
   - Decomposition of a compound – This is used to obtain a metal from a compound in which it occurs naturally, e.g. to obtain sodium by decomposing sodium chloride (common salt).
   - Electrorefining – Impure metal can be separated from impurities so a pure metal is obtained, e.g. purifying copper.
   - Electroplating – Coating a metal such as iron by another metal, such as silver, gold, nickel or zinc. The item being plated is placed at the cathode.
4. Galvanic cells involve spontaneous redox reactions, electrolytic cells involve non-spontaneous redox reactions.
   Galvanic cells change chemical energy to electrical energy.
   Electrolytic cells change electrical energy to chemical energy.
5. (a) The whole diagram is the galvanic (voltaic cell) in which a spontaneous redox reaction is taking place to produce electricity.



   (b) The galvanic/voltaic cell is the source of electricity which is forcing a non-spontaneous redox reaction to occur.



6. Various. Consult your teacher about the depth of treatment required and the preferred method of presentation.
7. (a) Electrolytic cell and voltaic(galvanic) cell.
   (b) Electrolytic cell.
   (c) Galvanic cell.
   (d) Anode.
   (e) Reduction.
   (f) Galvanic cell.
   (g) Galvanic/voltaic cell.

49 Revision of Electrolysis

1. B	2. C	3. A	4. B	5. D
6. D	7. C	8. A	9. C	10. D
11. D	12. B	13. A	14. B	15. B
16. B				

50 Investigations

1. (a) Red cabbage leaves will be more suitable as an indicator than rose petals because red cabbage leaf water shows a more definite colour change in acid and base.
   Note that the word 'better' should never be used in an hypothesis. Better requires a value judgement, it is not something that can be determined by a scientific experiment.
   (b) The pH of a strong acid is lower than the pH of a weak acid when both acids have the same concentration.
2. Various – more than one answer could be correct here. Note that your hypothesis has to be a testable statement – it does not have to be a correct statement – you will find that your hypothesis is supported or not supported by the results of your experiment.
   (a) When carbon dioxide gas dissolves in water the pH drops.
   When carbon dioxide dissolves in water the pH rises.
   (b) The addition of manganese dioxide to hydrogen peroxide will increase the rate at which it breaks down to water and oxygen gas.
   (c) A galvanic cell with a Zn | Zn^{2+} half-cell and a Ag | Ag^+ half-cell generate a higher voltage than a galvanic cell with a Zn | Zn^{2+} and Fe | Fe^{2+} half-cells.