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The Free High School Science Texts: Textbooks for High School Students Studying the Sciences
Chemistry
Grades 10 - 12

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Contents

Part IV

Chemical Systems

Chapter 18

The Water Cycle - Grade 10

18.1 Introduction

You may have heard the word 'cycle' many times before. Think for example of the word 'bicycle' or the regular 'cycle tests' that you may have at school. A cycle is a series of events that repeats itself. In the case of a bicycle, the wheel turns through a full circle before beginning the motion again, while cycle tests happen regularly, normally every week or every two weeks. Because a cycle repeats itself, it doesn't have a beginning or an end.

Our Earth is a **closed system**. This means that it can exchange *energy* with its surroundings (i.e. the rest of the solar system), but no new *matter* is brought into the system. For this reason, it is important that all the elements and molecules on Earth are recycled so that they are never completely used up. In the next two sections, we are going to take a closer look at two cycles that are very important for life on Earth. They are the **water cycle** and the **nitrogen cycle**.

18.2 The importance of water

For many people, it is so easy to take water for granted, and yet life on Earth would not exist were it not for this extraordinary compound. Not only is it believed that the first forms of life actually *started* in water, but most of the cells in living organisms contain between 70% and 95% water. Here in the cells, water acts as a solvent and helps to transport vital materials such as food and oxygen to where they are needed, and also removes waste products such as carbon dioxide and ammonia from the body. For many animals and plants, water is their home. Think for example of fish and amphibians that live either all or part of the time in rivers, dams and the oceans. In other words, if water did not exist, no life would be possible.

Apart from allowing life to exist, water also has a number of other functions. Water shapes the landscape around us by wearing away at rocks and also transports and deposits sediments on floodplains and along coastal regions. Water also plays a very important role in helping to regulate Earth's climate. We will discuss this again later in the chapter. As humans we use water in our homes, in industry, in mining, irrigation and even as a source of electricitiy in hydro-electric schemes. In fact, if we were able to view Earth from space, we would see that almost three quarters of our planet's surface is covered in water. It is because of this that Earth is sometimes called the 'Blue Planet'. Most of this water is stored in the oceans, with the rest found in ice (e.g. glaciers), groundwater (e.g. boreholes), surface water (e.g. rivers, lakes, estuaries, dams) and in the atmosphere as clouds and water vapour.

In the search for life on other planets, one of the first things that scientists look for is water. However, most planets are either too close to the sun (and therefore too hot) for water to exist in liquid form, or they are too far away and therefore too cold. So, even if water were to be found, the conditions are unlikely to allow it to exist in a form that can support the diversity of life that we see on Earth.

18.3 The movement of water through the water cycle

The water cycle is the continuous movement of water over, above, and beneath the Earth's surface. As water moves, it changes phase between liquid (water), solid (ice) and gas (water vapour). It is powered by solar energy and, because it is a cycle, it has no beginning or end.

Definition: The Water Cycle
The water cycle is the continuous circulation of water across the Earth. The water cycle is driven by solar radiation and it includes the atmosphere, land, surface water and groundwater. As water moves through the cycle, it changes state between liquid, solid, and gas phases. The actual movement of water from one part of the cycle to another (e.g. from river to ocean) is the result of processes such as evaporation, precipitation, infiltration and runoff.

The movement of water through the water cycle is shown in figure 18.1. In the figure, each process within this cycle is numbered. Each process will be described below.

1. **The source of energy**

   The water cycle is driven by the sun, which provides the heat energy that is needed for many of the other processes to take place.

2. **Evaporation**

   When water on the earth's surface is heated by the sun, the average energy of the water molecules increases and some of the molecules are able to leave the liquid phase and become water vapour. This is called evaporation. Evaporation is the change of water from a liquid to a gas as it moves from the ground, or from bodies of water like the ocean, rivers and dams, into the atmosphere.

3. **Transpiration**

   Transpiration is the evaporation of water from the aerial parts of plants, especially the leaves but also from the stems, flowers and fruits. This is another way that liquid water can enter the atmosphere as a gas.

4. **Condensation**

   When evaporation takes place, water vapour rises in the atmosphere and cools as the altitude (height above the ground) increases. As the temperature drops, the energy of the water vapour molecules also decreases, until the molecules don't have enough energy to stay in the gas phase. At this point, condensation occurs. Condensation is the change of water from water vapour (gas) into liquid water droplets in the air. *Clouds*, *fog* and *mist* are all examples of condensation. A cloud is actually a collection of lots and lots of tiny water droplets. This mostly takes place in the upper atmosphere but can also take place close to the ground if there is a significant temperature change.

Have you ever tried breathing out on a very cold day? It looks as though you are breathing out smoke! The moist air that you breathe out is much warmer than the air outside your body. As this warm, moist air comes into

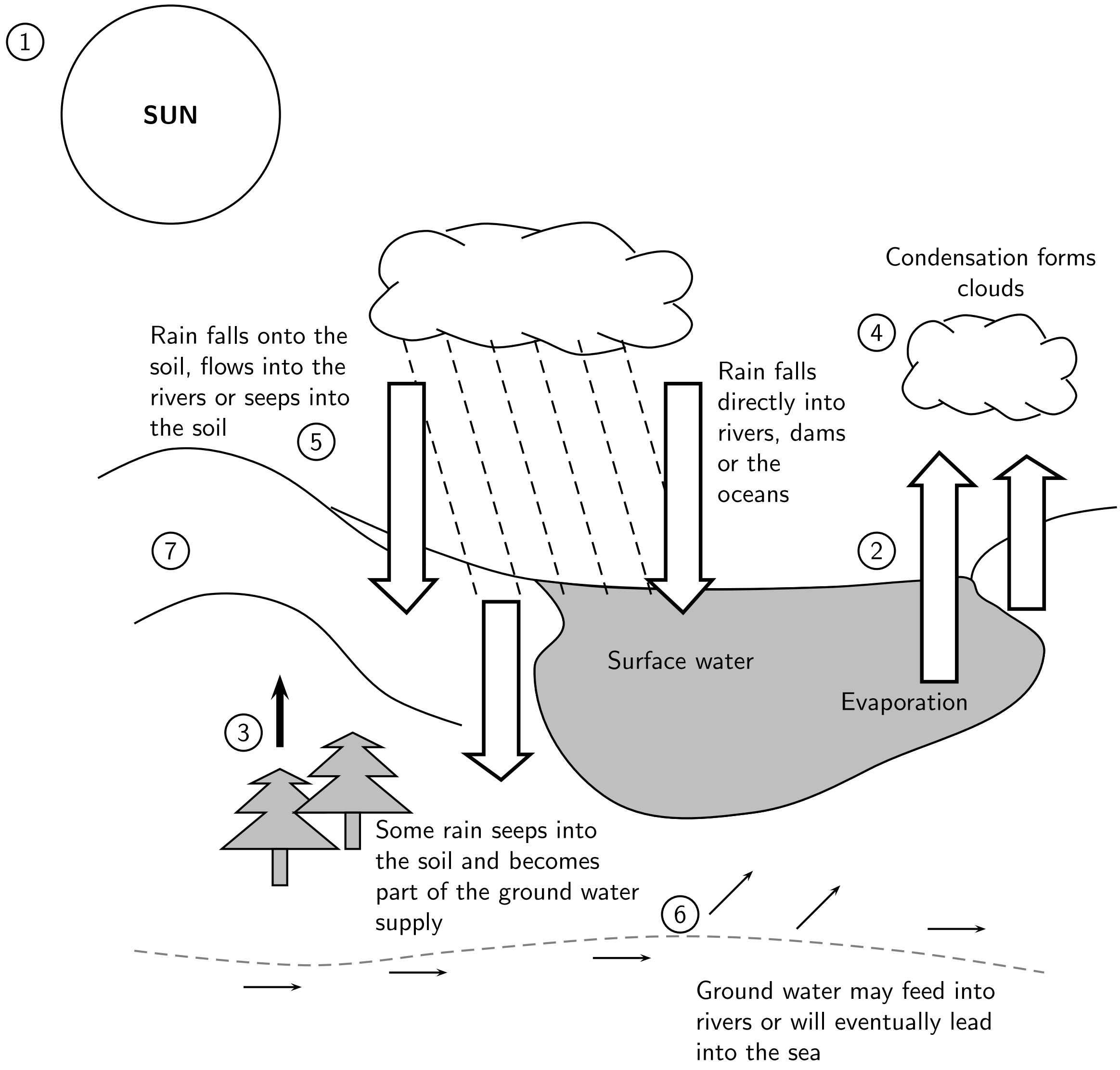


Figure 18.1: The water cycle

contact with the colder air outside, its temperature drops very quickly and the water vapour in the air you breathe out condenses. The 'smoke' that you see is actually formed in much the same way as clouds form in the upper atmosphere.

5. **Precipitation**

   Precipitation occurs when water falls back to the earth's surface in the form of rain or snow. Rain will fall as soon as a cloud becomes too saturated with water droplets. Snow is similar to rain, except that it is frozen. Snow only falls if temperatures in the atmosphere are around freezing. The freeing point of water is 0^0C).

6. **Infiltration**

   If precipitation occurs, some of this water will filter into the soil and collect underground. This is called infiltration. This water may evaporate again from the soil at a later stage, or the underground water may seep into another water body.

7. **Surface runoff**

   This refers to the many ways that water moves across the land. This includes *surface runoff* such as when water flows along a road and into a drain, or when water flows straight across the sand. It also includes *channel runoff* when water flows in rivers and streams. As it flows, the water may infiltrate into the ground, evaporate into the air, become stored in lakes or reservoirs, or be extracted for agricultural or other human uses.

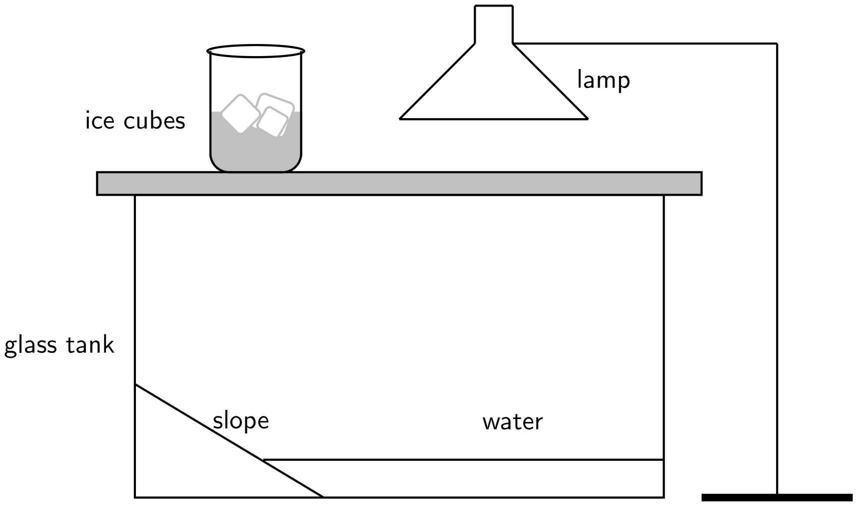
Important: It is important to realise that the water cycle is all about **energy exchanges**. The sun is the original energy *source*. Energy from the sun heats the water and causes evaporation. This energy is stored in water vapour as *latent heat*. When the water vapour condenses again, the latent heat is released, and helps to drive circulation in the atmosphere. The liquid water falls to earth, and will evaporate again at a later stage. The atmospheric circulation patterns that occur because of these exchanges of heat are very important in influencing climate patterns.

Activity :: Experiment : The Water Cycle

Materials:

Tile or piece of plastic (e.g. lid of ice-cream container) to make a hill slope; glass fish tank with a lid; beaker with ice cubes; lamp; water

Set up a model of the water cycle as follows:



1. Lean the plastic against one side so that it creates a 'hill slope' as shown in the diagram.
2. Pour water into the bottom of the tank until about a quarter of the hill slope is covered.
3. Close the fish tank lid.
4. Place the beaker with ice on the lid directly above the hill slope.
5. Turn the lamp on and position it so that it shines over the water.
6. Leave the model like this for 20-30 minutes and then observe what happens. Make sure that you don't touch the lamp as it will be very hot!

Observation questions:

1. Which parts of the water cycle can you see taking place in the model?
2. Which parts of the water cycle are *not* represented in the model?

3. Can you think of how those parts that are not shown *could* be represented?
4. What is the energy source in the model? What would the energy source be in reality?
5. What do you think the function of the ice is in the beaker?

18.4 The microscopic structure of water

In many ways, water behaves very differently from other liquids. These properties are directly related to the microscopic structure of water, and more specifically to the *shape* of the molecule and its *polar nature*, and to the *bonds* that hold water molecules together.

18.4.1 The polar nature of water

Every water molecule is made up of one oxygen atom that is bonded to two hydrogen atoms. When atoms bond, the nucleus of each atom has an attractive force on the electrons of the other atoms. This 'pull' is stronger in some atoms than in others and is called the **electronegativity** of the atom. In a water molecule, the oxygen atom has a higher electronegativty than the hydrogen atoms and therefore attracts the electrons more strongly. The result is that the oxygen atom has a slightly negative charge and the two hydrogen atoms each have a slightly positive charge. The water molecule is said to be **polar** because the electrical charge is not evenly distributed in the molecule. One part of the molecule has a different charge to other parts. You will learn more about this in chapter 4.

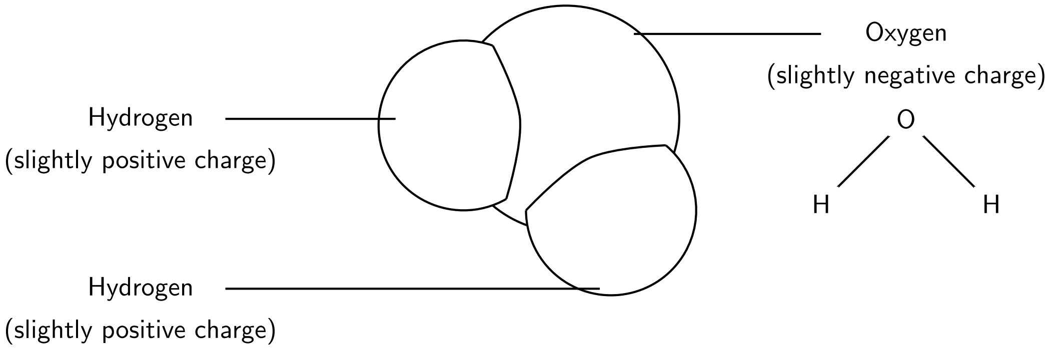


Figure 18.2: Diagrams showing the structure of a water molecule. Each molecule is made up of two hydrogen atoms that are attached to one oxygen atom.

18.4.2 Hydrogen bonding in water molecules

In every water molecule, the forces that hold the individual atoms together are called **intramolecular forces**. But there are also forces *between* different water molecules. These are called **intermolecular forces** (figure 18.3). You will learn more about these at a later stage, but for now it is enough to know that in water, molecules are held together by **hydrogen bonds**. Hydrogen bonds are a much stronger type of intermolecular force than those found in many other substances, and this affects the properties of water.

Important: Intramolecular and intermolecular forces

If you find these terms confusing, remember that 'intra' means *within* (i.e. the forces within a molecule). An **intro***vert* is someone who doesn't express emotions and feelings outwardly. They tend to be quieter and keep to themselves. 'Inter' means *between* (i.e. the forces between molecules). An **inter***national* cricket match is a match between two different countries.

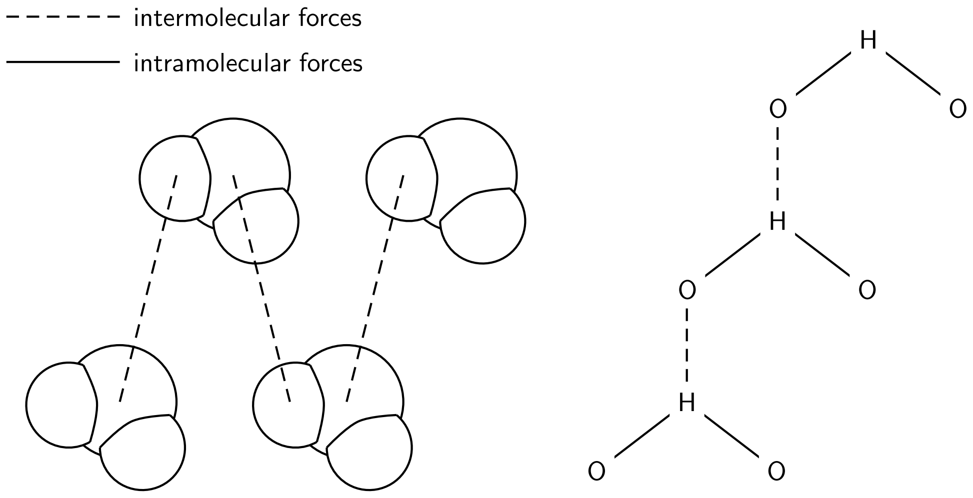


Figure 18.3: Intermolecular and intramolecular forces in water. Note that the diagram on the left only shows *intermolecular* forces. The intramolecular forces are between the atoms of each water molecule.

18.5 The unique properties of water

Because of its polar nature and the strong hydrogen bonds between its molecules, water has some special properties that are quite different to those of other substances.

1. **Absorption of infra-red radiation**

   The polar nature of the water molecule means that it is able to absorb infra-red radiation (heat) from the sun. As a result of this, the oceans and other water bodies act as heat reservoirs, and are able to help moderate the Earth's climate.

2. **Specific heat**

   Definition: Specific heat
   Specific heat is the amount of heat energy that is needed to increase the temperature of a substance by one degree.

   Water has a high specific heat, meaning that a lot of energy must be absorbed by water before its temperature changes.

Activity :: Demonstration : The high specific heat of water

(a) Pour about 100 ml of water into a glass beaker.
(b) Place the beaker on a stand and heat it over a bunsen burner for about 2 minutes.
(c) After this time, carefully touch the side of the beaker (Make sure you touch the glass very lightly because it will be very hot and may burn you!). Then use the end of a finger to test the temperature of the water.

What do you notice? Which of the two (glass or water) is the hottest?

You have probably observed this phenomenon if you have boiled water in a pot on the stove. The metal of the pot heats up very quickly, and can burn your fingers if you touch it, while the water may take several minutes before its temperature increases even slightly. How can we explain this in terms of hydrogen bonding? Remember that increasing the temperature of a substance means that its particles will move more quickly. However, before they can move faster, the bonds between them must be broken. In the case of water, these bonds are strong hydrogen bonds, and so a lot of energy is needed just to break these, before the particles can start moving faster.

It is the high specific heat of water and its ability to absorb infra-red radiation that allows it to regulate climate. Have you noticed how places that are closer to the sea have less extreme daily temperatures than those that are inland? During the day, the oceans heat up slowly, and so the air moving from the oceans across land is cool. Land temperatures are cooler than they would be if they were further from the sea. At night, the oceans lose the heat that they have absorbed very slowly, and so sea breezes blowing across the land are relatively warm. This means that at night, coastal regions are generally slightly warmer than areas that are further from the sea.

By contrast, places further from the sea experience higher maximum temperatures, and lower minimum temperatures. In other words, their *temperature range* is higher than that for coastal regions. The same principle also applies on a *global* scale. The large amount of water across Earth's surface helps to regulate temperatures by storing infra-red radiation (heat) from the sun, and then releasing it very slowly so that it never becomes too hot or too cold, and life is able to exist comfortably. In a similar way, water also helps to keep the temperature of the *internal* environment of living organisms relatively constant. This is very important. In humans, for example, a change in body temperature of only a few degrees can be deadly.

3. **Melting point and boiling point**

   The melting point of water is 0^0C and its boiling point is 100^0C. This large difference between the melting and boiling point is very important because it means that water can exist as a liquid over a large range of temperatures. The three phases of water are shown in figure 18.4.

4. **High heat of vaporisation**

Definition: Heat of vaporisation
Heat of vaporisation is the energy that is needed to change a given quantity of a substance into a gas.

The strength of the hydrogen bonds between water molecules also means that it has a high heat of vaporisation. 'Heat of vaporisation' is the heat energy that is needed to change water from the liquid to the gas phase. Because the bonds between molecules are strong, water has to be heated to 100^0C before it changes phase. At this temperature, the molecules have enough energy to break the bonds that hold the molecules together. The heat of vaporisation for water is 40.65 kJ/mol. It is very lucky for life on earth that water does have a high heat of vaporisation. Can you imagine what a problem it would be if water's heat of vaporisation was much lower? All the water that makes up the cells in our bodies would evaporate and most of the water on earth would no longer be able to exist as a liquid!

5. **Less dense solid phase**

   Another unusual property of water is that its solid phase (ice) is *less dense* than its liquid phase. You can observe this if you put ice into a glass of water. The ice doesn't sink to

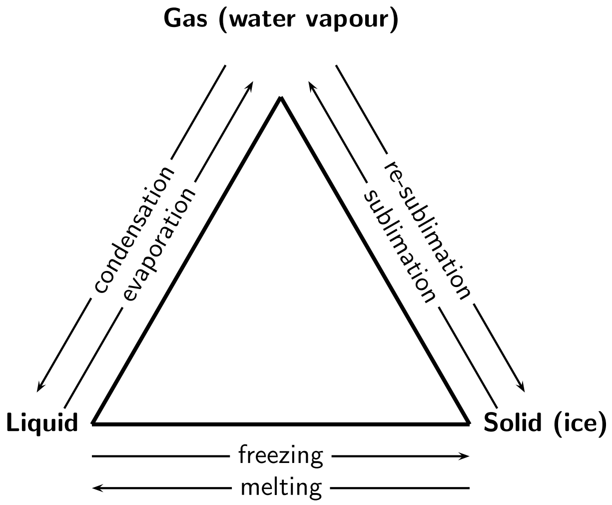


Figure 18.4: Changes in phase of water

the bottom of the glass, but floats on top of the liquid. This phenomenon is also related to the hydrogen bonds between water molecules. While other materials contract when they solidify, water expands. The ability of ice to float as it solidifies is a very important factor in the environment. If ice sank, then eventually all ponds, lakes, and even the oceans would freeze solid as soon as temperatures dropped below freezing, making life as we know it impossible on Earth. During summer, only the upper few inches of the ocean would thaw. Instead, when a deep body of water cools, the floating ice insulates the liquid water below, preventing it from freezing and allowing life to exist under the frozen surface.

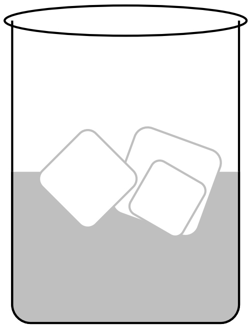


Figure 18.5: Ice cubes floating in water

Antarctica, the 'frozen continent', has one of the world's largest and deepest freshwater lakes. And this lake is hidden beneath 4 kilometres of ice! Lake Vostok is 200 km long and 50 km wide. The thick, glacial blanket of ice acts as an insulator, preventing the water from freezing.

6. **Water as a solvent**

Water is also a very good solvent, meaning that it is easy for other substances to dissolve in it. It is very seldom, in fact, that we find pure water. Most of the time, the water that we drink and use has all kinds of substances dissolved in it. It is these that make water taste different in different areas. So why, then, is it important that water is such a good solvent? We will look at just a few examples.

- Firstly, think about the animals and plants that live in aquatic environments such as rivers, dams or in the sea. All of these living organisms either need oxygen for respiration or carbon dioxide for photosynthesis, or both. How do they get these gases from the water in which they live? Oxygen and carbon dioxide are just two of the substances that dissolve easily in water, and this is how plants and animals obtain the gases that they need to survive. Instead of being available as gases in the atmosphere, they are present in solution in the surrounding water.
- Secondly, consider the fact that all plants need nitrogen to grow, and that they absorb this nitrogen from compounds such as nitrates and nitrates that are present in the soil. The question remains, however, as to how these nitrates and nitrites are able to be present in the soil at all, when most of the Earth's nitrogen is in a gaseous form in the atmosphere. Part of the answer lies in the fact that nitrogen oxides, which are formed during flashes of lightning, can be dissolved in rainwater and transported into the soil in this way, to be absorbed by plants. The other part of the answer lies in the activities of nitrogen-fixing bacteria in the soil, but this is a topic that we will return to in a later section.

It should be clear now, that water is an amazing compound, and that without its unique properties, life on Earth would definitely not be possible.

Exercise: The properties of water

1. A learner returns home from school on a hot afternoon. In order to get cold water to drink, she adds ice cubes to a glass of water. She makes the following observations:
   - The ice cubes float in the water.
   - After a while the water becomes cold and the ice cubes melt.

   (a) What property of ice cubes allows them to float in the water?
   (b) Briefly explain why the water gets cold when the ice cubes melt.
   (c) Briefly describe how the property you mentioned earlier affects the survival of aquatic life during winter.
2. Which properties of water allow it to remain in its liquid phase over a large temperature range? Explain why this is important for life on earth.

18.6 Water conservation

Water is a very precious substance and yet far too often, earth's water resources are abused and taken for granted. How many times have you walked past polluted rivers and streams, or seen the flow of water in a river reduced to almost nothing because of its extraction for industrial and other uses? And if you were able to test the *quality* of the water you see, you would probably be shocked. Often our water resources are contaminated with chemicals such as pesticides and fertilisers. If water is to continue playing all the important functions that were discussed earlier, it is vital that we reduce the impact of humans on these resources.

Activity :: Group work : Human impacts on the water cycle

Read the following extract from an article, entitled 'The Effects of Urbanisation on the Water Cycle' *by Susan Donaldson, and then answer the questions that follow.*

> As our communities grow, we notice many visible changes including housing developments, road networks, expansion of services and more. These changes have an impact on our precious water resources, with *pollution* of water being one of many such impacts. To understand these impacts you will need to have a good knowledge of the water cycle!
> It is interesting to note that the oceans contain most of earth's water (about 97%). Of the freshwater supplies on earth, 78% is tied up in polar ice caps and snow, leaving only a very small fraction available for use by humans. Of the available fresh water, 98% is present as groundwater, while the remaining 2% is in the form of surface water. Because our usable water supply is so limited, it is vitally important to protect water *quality*. Within the water cycle, there is no 'new' water ever produced on the earth. The water we use today has been in existence for billions of years. The water cycle continually renews and refreshes this finite water supply.
> So how exactly does urbanisation affect the water cycle? The increase in hard surfaces (e.g. roads, roofs, parking lots) decreases the amount of water that can soak into the ground. This increases the amount of surface runoff. The runoff water will collect many of the pollutants that have accumulated on these surfaces (e.g. oil from cars) and carry them into other water bodies such as rivers or the ocean. Because there is less infiltration, peak flows of stormwater runoff are larger and arrive earlier, increasing the size of urban floods. If groundwater supplies are reduced enough, this may affect stream flows during dry weather periods because it is the groundwater that seeps to the surface at these times.
> Atmospheric pollution can also have an impact because condensing water vapour will pick up these pollutants (e.g. SO_2, CO_2 and NO_2) and return them to earth into other water bodies. However, while the effects of urbanisation on water quality can be major, these impacts can be reduced if wise decisions are made during the process of development.

Questions

1. In groups, try to explain...
   (a) what is meant by 'urbanisation'
   (b) how urbanisation can affect water quality
2. Explain why it is so important to preserve the quality of our water supplies.
3. The article gives some examples of human impacts on water quality. In what *other* ways do human activities affect water quality?
4. What do you think some of the *consequences* of these impacts might be for humans and other forms of life?
5. Imagine that you are the city manager in your own city or the city closest to you. What changes would you introduce to try to protect the quality of water resources in your urban area?
6. What measures could be introduced in rural areas to protect water quality?

Apart from the *pollution* of water resources, the *overuse* of water is also a problem. In looking at the water cycle, it is easy sometimes to think that water is a never-ending resource. In a sense this is true because water cannot be destroyed. However, the *availability* of water may vary from place to place. In South Africa for example, many regions are extremely dry and receive very little rainfall. The same is true for many other parts of the world, where the scarcity of water is a life and death issue. The present threat of **global warming** is also likely to affect water resources. Some climate models suggest that rising temperatures could increase the variability of climate and decrease rainfall in South Africa. With this in mind, and remembering that South Africa is already a dry country, it is vitally important that we manage our water use carefully. In addition to this, the less water there is available, the more likely it is that water *quality* will also decrease. A decrease in water quality limits how water can be used and developed.

At present, the demands being placed on South Africa's water resources are large. Table 18.1 shows the water requirements that were predicted for the year 2000. The figures in the table were taken from South Africa's *National Water Resource Strategy*, produced by the Department of Water Affairs and Forestry in 2004. In the table, 'rural' means water for domestic use and stock watering in rural areas, while 'urban' means water for domestic, industrial and commercial use in the urban area. 'Afforestation' is included because many plantations reduce stream flow because of the large amounts of water they need to survive.

Table 18.1: The predicted water requirements for various water management areas in South Africa for 2000 (million m^3/annum)

Water management area	Irrigation	Urban	Rural	Mining and bulk industrial	Power generation	Afforestation	Total
Limpopo	238	34	28	14	7	1	322
Thukela	204	52	31	46	1	0	334
Upper Vaal	114	635	43	173	80	0	1045
Upper Orange	780	126	60	2	0	0	968
Breede	577	39	11	0	0	6	633
Country total	**7920**	**2897**	**574**	**755**	**297**	**428**	**12871**

Activity :: Case Study : South Africa's water requirements
Refer to table 18.1 and then answer the following questions:

1. Which water management area in South Africa has the highest need for water...
   (a) in the *mining and industry* sector?
   (b) for *power generation*?
   (c) in the *irrigation* sector?
   (d) Suggest reasons for each of your answers above.
2. For South Africa as a whole...
   (a) Which activity uses the *most* water?
   (b) Which activity uses the *least* water?
3. Complete the following table, by calculating the percentage (%) that each activity contributes to the total water requirements in South Africa for the year 2000.

Water use activity	% of SA's total water requirements
Irrigation	
Urban	
Rural	
Mining and bulk industry	
Power generation	
Afforestation	

Table 18.2: The available water yield in South Africa in 2000 for various water management areas (million m^3/annum)

Water management area	Surface water	Ground	Irrigation	Urban	Mining and bulk industrial	Total local yield
Limpopo	160	98	8	15	0	281
Thukela	666	15	23	24	9	737
Upper Vaal	598	32	11	343	146	1130
Upper Orange	4311	65	34	37	0	4447
Breede	687	109	54	16	0	866
Country total	**10240**	**1088**	**675**	**970**	**254**	**13227**

Now look at table 18.2, which shows the amount of water *available* in South Africa during 2000. In the table, 'usable return flow' means the amount of water that can be reused after it has been used for irrigation, urban or mining.

Activity :: Case Study : Water conservation
Refer to table 18.2 and then answer the following questions:

1. Explain what is meant by...
   (a) surface water
   (b) ground water
2. Which water management area has the...
   (a) lowest surface water yield?
   (b) highest surface water yield?
   (c) lowest *total* yield?
   (d) highest *total* yield?
3. Look at the country's *total water requirements* for 2000 and the *total available yield*.
   (a) Calculate what percentage of the country's water yield is already being used up.
   (b) Do you think that the country's total water requirements will increase or decrease in the coming years? Give a reason for your answer.
4. South Africa is already placing a huge strain on existing water resources. In groups of 3-4, discuss ways that the country's demand for water could be reduced. Present your ideas to the rest of the class for discussion.

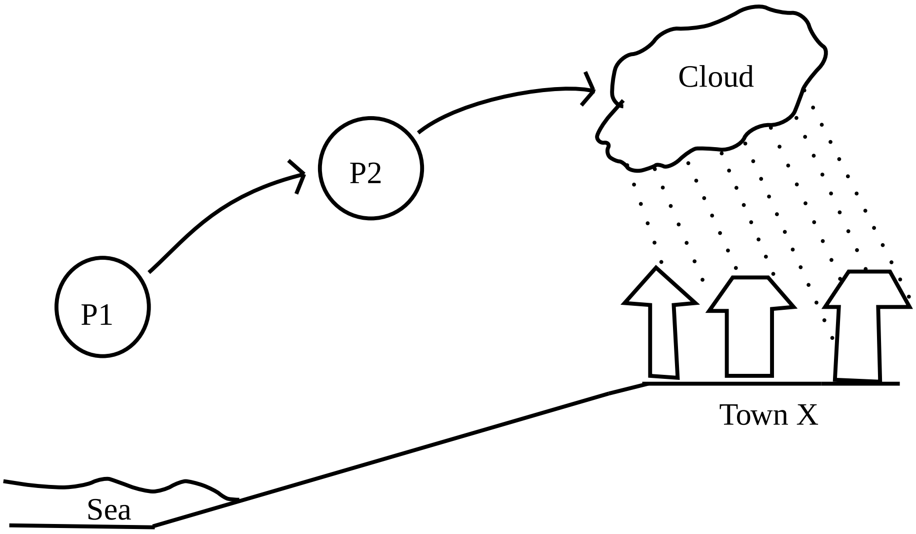
18.7 Summary

- Water is critical for the survival of life on Earth. It is an important part of the cells of living organisms and is used by humans in homes, industry, mining and agriculture.
- Water moves between the land and sky in the **water cycle**. The water cycle describes the changes in phase that take place in water as it circulates across the Earth. The water cycle is driven by solar radiation.

- Some of the important processes that form part of the water cycle are evaporation, transpiration, condensation, precipitation, infiltration and surface runoff. Together these processes ensure that water is cycled between the land and sky.
- It is the microscopic structure of water that determines its unique properties.
- Water molecules are **polar** and are held together by **hydrogen bonds**. These characteristics affect the properties of water.
- Some of the unique properties of water include its ability to absorb infra-red radiation, its high specific heat, high heat of vaporisation and the fact that the solid phase of water is less dense that its liquid phase.
- These properties of water help it to sustain life on Earth by moderating climate, regulating the internal environment of living organisms and allowing liquid water to exist below ice, even if temperatures are below zero.
- Water is also a good **solvent**. This property means that it is a good transport medium in the cells of living organisms, and that it can dissolve gases and other compounds that may be needed by aquatic plants and animals.
- Human activities threaten the quality of water resources through pollution and altered runoff patterns.
- As human populations grow, there is a greater demand for water. In many areas, this demand exceeds the amount of water available for use. Managing water wisely is important in ensuring that there will always be water available both for human use, and to maintain natural ecosystems.

Exercise: Summary Exercise

1. Give a word or term for each of the following phrases:
    (a) The continuous circulation of water across the earth.
    (b) The change in phase of water from gas to liquid.
    (c) The movement of water across a land surface.
    (d) The temperature at which water changes from liquid to gas.
2. In each of the following multiple choice questions, choose the one correct answer from the list provided.
    (a) Many of the unique properties of water (e.g. its high specific heat and high boiling point) are due to:
        i. strong covalent bonds between the hydrogen and oxygen atoms in each water molecule
        ii. the equal distribution of charge in a water molecule
        iii. strong hydrogen bonds between water molecules
        iv. the linear arrangement of atoms in a water molecule
    (b) Which of the following statements is **false**?
        i. Most of the water on earth is in the oceans.
        ii. The hardening of surfaces in urban areas results in increased surface runoff.
        iii. Water conservation is important because water cannot be recycled.
        iv. Irrigation is one of the largest water users in South Africa.
3. The sketch below shows a process that leads to rainfall in town X. The town has been relying only on rainfall for its water supply because it has no access to rivers or tap water. A group of people told the community that they will never run out of rainwater *because it will never stop raining*.



(a) List the processes labelled P_1 and P_2 that lead to rainfall in town X.

(b) Is this group of people correct in saying that town X will never run out of rainwater? Justify your answer using the sketch.

Recently, the amount of rainwater has decreased significantly. Various reasons have been given to explain the drought. Some of the community members are blaming this group who told them that it will never stop raining.

(c) What scientific arguments can you use to convince the community members that this group of people should not be blamed for the drought?

(d) What possible strategies can the community leaders adopt to ensure that they have a regular supply of water.

Chapter 19

Global Cycles: The Nitrogen Cycle - Grade 10

19.1 Introduction

The earth's atmosphere is made up of about 78% nitrogen, making it the largest pool of this gas. Nitrogen is essential for many biological processes. It is in all amino acids, proteins and nucleic acids. As you will see in a later chapter, these compounds are needed to build tissues, transport substances around the body, and control what happens in living organisms. In plants, much of the nitrogen is used in chlorophyll molecules which are needed for photosynthesis and growth.

So, if nitrogen is so essential for life, how does it go from being a gas in the atmosphere to being part of living organisms such as plants and animals? The problem with nitrogen is that it is an 'inert' gas, which means that it is unavailable to living organisms in its gaseous form. This is because of the strong triple bond between its atoms that makes it difficult to break. Something needs to happen to the nitrogen gas to change it into a form that it can be used. And at some later stage, these new compounds must be converted back into nitrogen gas so that the amount of nitrogen in the atmosphere stays the same. This process of changing nitrogen into different forms is called the **nitrogen cycle** (figure 19.1).

Definition: The nitrogen cycle
The nitrogen cycle is a biogeochemical cycle that describes how nitrogen and nitrogen-containing compounds are changed in nature.

Very broadly, the nitrogen cycle is made up of the following processes:

- **Nitrogen fixation** - The process of converting inert nitrogen gas into more useable nitrogen compounds such as ammonia.
- **Nitrification** - The conversion of ammonia into nitrites and then into nitrates, which can be absorbed and used by plants.
- **Denitrification** - The conversion of nitrates back into nitrogen gas in the atmosphere.

We are going to look at each of these processes in more detail.

19.2 Nitrogen fixation

Nitrogen fixation is needed to change gaseous nitrogen into forms such as ammonia that are more useful to living organisms. Some fixation occurs in lightning strikes and in industrial processes,

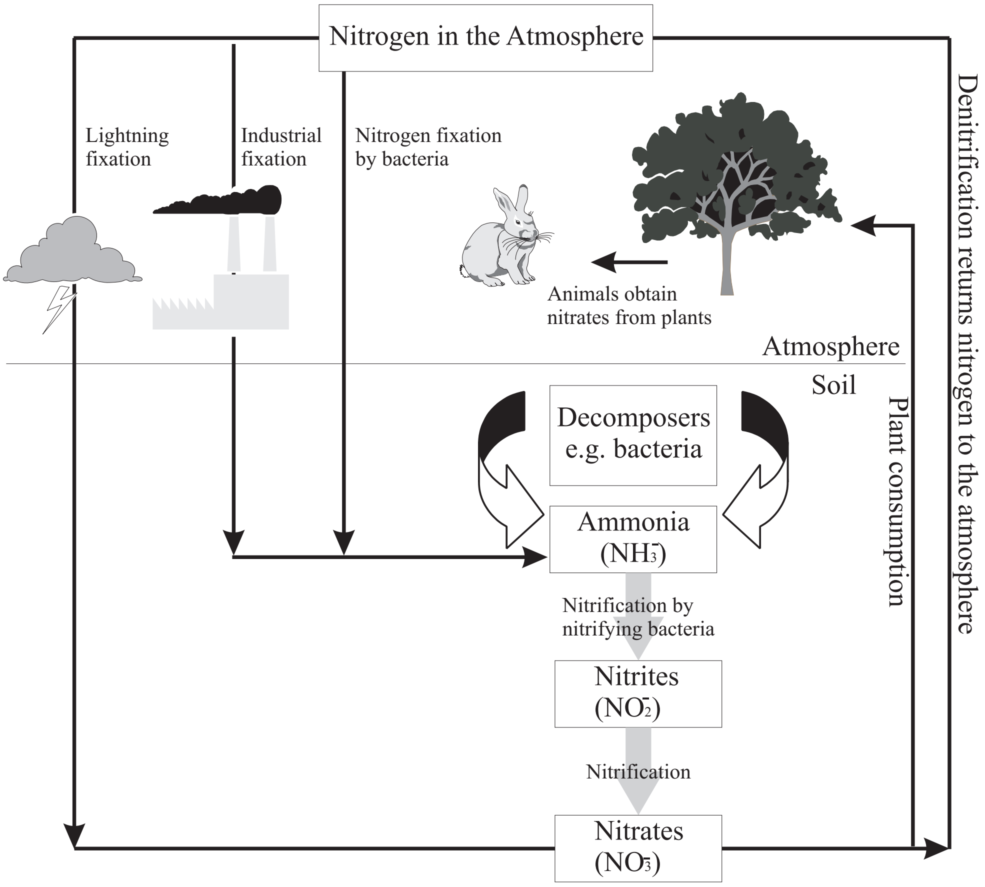


Figure 19.1: A simplified diagram of the nitrogen cycle

but most fixation is done by different types of bacteria living either in the soil or in parts of the plants.

1. **Biological fixation**

   Some bacteria are able to fix nitrogen. They use an enzyme called *nitrogenase* to combine gaseous nitrogen with hydrogen to form ammonia. The bacteria then use some of this ammonia to produce their own organic compounds, while what is left of the ammonia becomes available in the soil.

   Some of these bacteria are free-living, in other words they live in the soil. Others live in the root nodules of legumes (e.g. soy, peas and beans). Here they form a mutualistic relationship with the plant. The bacteria get carbohydrates (food) from the plant and, in exchange, produce ammonia which can be converted into nitrogen compounds that are essential for the survival of the plant. In nutrient-poor soils, planting lots of legumes can help to enrich the soil with nitrogen compounds.

   A simplified equation for biological nitrogen fixation is:

   $$N_2 + 8H^+ + 8e^- \rightarrow 2NH_3 + H_2$$

   Energy is used in the process, but this is not shown in the above equation.

   Another important source of ammonia in the soil is **decomposition**. When animals and plants die, the nitrogen compounds that were present in them are broken down and converted into ammonia. This process is carried out by decomposition bacteria and fungi in the soil.

2. **Industrial nitrogen fixation**

In the Haber-Bosch process, nitrogen (N_2) is converted together with hydrogen gas (H_2) into ammonia (NH_3) fertiliser. This is an artificial process.

3. **Lightning**

   In the atmosphere, lightning and photons are important in the reaction between nitrogen (N_2) and oxygen (O_2) to form nitric oxide (NO) and then nitrates.

It is interesting to note that by cultivating legumes, using the Haber-Bosch process to manufacture chemical fertilisers and increasing pollution from vehicles and industry, humans have more than doubled the amount of nitrogen that would normally be changed from nitrogen gas into a biologically useful form. This has serious environmental consequences.

19.3 Nitrification

Nitrification involves two biological oxidation reactions: firstly, the oxidation of ammonia with oxygen to form nitrite (NO_2^-) and secondly the oxidation of these nitrites into nitrates.

1. $NH_3 + O_2 \rightarrow NO_2^- + 3H^+ + 2e^-$ (production of *nitrites*)
2. $NO_2^- + H_2O \rightarrow NO_3^- + 2H^+ + 2e^-$ (production of *nitrates*)

Nitrification is an important step in the nitrogen cycle in soil because it converts the ammonia (from the nitrogen fixing part of the cycle) into nitrates, which are easily absorbed by the roots of plants. This absorption of nitrates by plants is called **assimilation**. Once the nitrates have been assimilated by the plants, they become part of the plants' proteins. These plant proteins are then available to be eaten by animals. In other words, animals (including humans) obtain their own nitrogen by feeding on plants. Nitrification is performed by bacteria in the soil, called *nitrifying bacteria*.

Activity :: Case Study : Nitrates in drinking water

Read the information below and then carry out your own research to help you answer the questions that follow.

The negatively charged nitrate ion is not held onto soil particles and so can be easily washed out of the soil. This is called **leaching**. In this way, valuable nitrogen can be lost from the soil, reducing the soil's fertility. The nitrates can then accumulate in groundwater, and eventually in drinking water. There are strict regulations that control how much nitrate can be present in drinking water, because nitrates can be reduced to highly reactive nitrites by microorganisms in the gut. Nitrites are absorbed from the gut and bind to haemoglobin (the pigment in blood that helps to transport oxygen around the body). This reduces the ability of the haemoglobin to carry oxygen. In young babies this can lead to respiratory distress, a condition known as "blue baby syndrome".

1. How is nitrate concentration in water measured?
2. What concentration of nitrates in drinking water is considered acceptable? You can use drinking water standards for any part of the world, if you can't find any for South Africa.
3. What is 'blue baby syndrome' and what are the symptoms of the disease?

19.4 Denitrification

Denitrification is the process of reducing nitrate and nitrite into gaseous nitrogen. The process is carried out by *denitrification bacteria*. The nitrogen that is produced is returned to the atmosphere to complete the nitrogen cycle.

The equation for the reaction is:

$$2NO_3^- + 10e^- + 12H^+ \rightarrow N_2 + 6H_2O$$

19.5 Human Influences on the Nitrogen Cycle

Humans have contributed significantly to the nitrogen cycle in a number of ways.

- Both **artificial fertilisation** and the planting of **nitrogen fixing crops**, increase the amount of nitrogen in the soil. In some ways this has positive effects because it increases the fertility of the soil, and means that agricultural productivity is high. On the other hand, however, if there is too much nitrogen in the soil, it can run off into nearby water courses such as rivers, or can become part of the groundwater supply as we mentioned earlier. Increased nitrogen in rivers and dams can lead to a problem called **eutrophication**. Eutrophication is a process where water bodies such as rivers, estuaries, dams and slow-moving streams receive *excess* nutrients (e.g. nitrogen and phosphorus compounds) that stimulate excessive plant growth. Sometimes this can cause certain plant species to be favoured over the others and one species may 'take over' the ecosystem, resulting in a decrease in plant diversity. This is called a 'bloom'. Eutrophication also affects water quality. When the plants die and decompose, large amounts of oxygen are used up and this can cause other animals in the water to die.

Activity :: Case Study : Fertiliser use in South Africa

Refer to the data table below, which shows the average fertiliser use (in kilograms per hectare or kg/ha) over a number of years for South Africa and the world. Then answer the questions that follow:

	1965	**1970**	**1975**	**1980**	**1985**	**1990**	**1995**	**2000**	**2002**
SA	27.9	42.2	57.7	80.3	66.6	54.9	48.5	47.1	61.4
World	34.0	48.9	63.9	80.6	86.7	90.9	84.9	88.2	91.9

1. On the same set of axes, draw two line graphs to show how fertiliser use has changed in SA and the world between 1965 and 2002.
2. Describe the trend you see for...
   (a) the world
   (b) South Africa
3. Suggest a reason why the world's fertiliser use has changed in this way over time.
4. Do you see the same pattern for South Africa?
5. Try to suggest a reason for the differences you see in the fertiliser use data for South Africa.
6. One of the problems with increased fertiliser use is that there is a greater chance of nutrient runoff into rivers and dams, and therefore a greater danger of eutrophication. In groups of 5-6, discuss the following questions:
   (a) What could farmers do to try to reduce the risk of nutrient runoff from fields into water systems? Try to think of at least 3 different strategies that they could use.

(b) Imagine you are going to give a presentation on eutrophication to a group of farmers who know nothing about it. How will you educate them about the dangers? How will you convince them that it is in their interests to change their farming practices? Present your ideas to the class.

- **Atmospheric pollution** is another problem. The main culprits are nitrous oxide (N_2O), nitric oxide (NO) and nitrogen dioxide (NO_2). Most of these gases result either from emissions from agricultural soils (and particularly artificial fertilisers), or from the combustion of fossil fuels in industry or motor vehicles. The combustion (burning) of nitrogen-bearing fuels such as coal and oil releases this nitrogen as N_2 or NO gases. Both NO_2 and NO can combine with water droplets in the atmosphere to form **acid rain**. Furthermore, both NO and NO_2 contribute to the depletion of the ozone layer and some are **greenhouse gases**. In high concentrations these gases can contribute towards **global warming**.

19.6 The industrial fixation of nitrogen

A number of industrial processes are able to fix nitrogen into different compounds and then convert these compounds into fertilisers. In the descriptions below, you will see how atmospheric nitrogen is fixed to produce ammonia, how ammonia is then reacted with oxygen to form nitric acid and how nitric acid and ammonia are then used to produce the fertiliser, ammonium nitrate.

- **Preparation of ammonia (NH_3)**

  The industrial preparation of ammonia is known as the **Haber-Bosch process**. At a high pressure and a temperature of approximately 500^0C, and in the presence of a suitable catalyst (usually iron), nitrogen and hydrogen react according to the following equation:

  $$N_2 + 3H_2 \rightarrow 2NH_3$$

  Ammonia is used in the preparation of artficial fertilisers such as $(NH_4)_2SO_4$ and is also used in cleaning agents and cooling installations.

Interesting Fact

Fritz Haber and Carl Bosch were the two men responsible for developing the Haber-Bosch process. In 1918, Haber was awarded the Nobel Prize in Chemistry for his work. The Haber-Bosch process was a milestone in industrial chemistry because it meant that nitrogenous fertilisers were cheaper and much more easily available. At the time, this was very important in providing food for the growing human population.

Haber also played a major role in the development of chemical warfare in World War I. Part of this work included the development of gas masks with absorbent filters. He also led the teams that developed chlorine gas and other deadly gases for use in trench warfare. His wife, Clara Immerwahr, also a chemist, opposed his work on poison gas and committed suicide with his service weapon in their garden. During the 1920s, scientists working at his institute also developed the cyanide gas formulation Zyklon B, which was used as an insecticide and also later, after he left the programme, in the Nazi extermination camps.

Haber was Jewish by birth, but converted from Judaism in order to be more accepted in Germany. Despite this, he was forced to leave the country in 1933 because he was Jewish 'by definition' (his mother was Jewish). He died in 1934 at the age of 65. Many members of his extended family died in the Nazi concentration camps, possibly gassed by Zyklon B.

- **Preparation of nitric acid (HNO_3)**

  Nitric acid is used to prepare fertilisers and explosives. The industrial preparation of nitric acid is known as the **Ostwald process**. The Ostwald process involves the conversion of ammonia into nitric acid in various stages:

  Firstly, ammonia is heated with oxygen in the presence of a platinum catalyst to form nitric oxide and water.

  $$4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g)$$

  Secondly, nitric oxide reacts with oxygen to form nitrogen dioxide. This gas is then readily absorbed by the water to produce nitric acid. A portion of nitrogen dioxide is reduced back to nitric oxide.

  $$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$$
  $$3NO_2(g) + H_2O(l) \rightarrow 2HNO_3(aq) + NO(g)$$

  The NO is recycled, and the acid is concentrated to the required strength by a process called *distillation*.

- **Preparation of ammonium nitrate**

  Ammonium nitrate is used as a fertiliser, as an explosive and also in the preparation of 'laughing gas' which is used as an anaesthetic. Ammonium nitrate is prepared by reacting ammonia with nitric acid:

  $$NH_3 + HNO_3 \rightarrow NH_4NO_3$$

Activity :: Debate : Fertiliser use
Divide the class into two groups to debate the following topic:

Increasing the use of artificial fertilisers is the best solution to meet the growing food needs of the world's human population.

One group should take the position of *agreeing* with the statement, and the other should *disagree*. In your groups, discuss reasons why you have the opinion that you do, and record some notes of your discussion. Your teacher will then explain to you how to proceed with the debate.

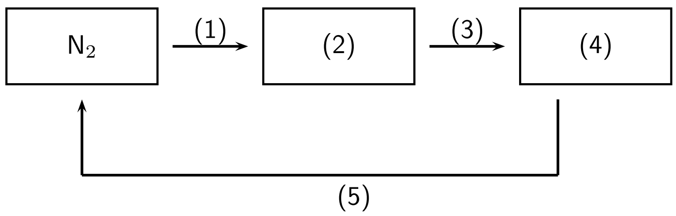
19.7 Summary

- **Nitrogen** is essential for life on earth, since it forms part of **amino acids**, **proteins** and **nucleic acids**.
- The **atmosphere** is composed mostly of nitrogen gas, but the gas is **inert**, meaning that it is not available to living organisms in its gaseous form.
- The **nitrogen cycle** describes how nitrogen and nitrogen-containing compounds are changed into different forms in nature.

- The nitrogen cycle consists of three major processes: **nitrogen fixation**, **nitrification** and **denitrification**.
- **Nitrogen fixation** is the conversion of atmospheric nitrogen into compounds such as ammonia, that are more easily used.
- Nitrogen can be fixed **biologically** through the actions of **bacteria**, **industrially** through the **Haber-Bosch process** or by **lightning**.
- **Nitrification** converts ammonia into **nitrites** and **nitrates**, which can be easily **assimilated** by plants.
- **Denitrification** converts nitrites and nitrates back into gaseous nitrogen to complete the nitrogen cycle.
- **Humans** have had a number of **impacts** on the nitrogen cycle. The production of **artificial fertilisers** for example, means that there is a greater chance of runoff into water systems. In some cases, **eutrophication** may occur.
- **Eutrophication** is the enrichment of water systems with excess nutrients, which may stimulate excessive plant growth at the expense of other parts of the ecosystem.
- Many nitrogen gases such as NO, N_2O and NO_2 are released by agricultural soils and artificial fertilisers. These gases may combine with water vapour in the atmosphere and result in **acid rain**. Some of these gases are also greenhouse gases and may contribute towards **global warming**.
- A number of **industrial processes** are used to produce **articifical fertilisers**.
- The **Haber-Bosch process** converts atmsopheric nitrogen into **ammonia**.
- The **Ostwald process** reacts ammonia with oxygen to produce **nitric acid**, which is used in the preparation of fertilisers and explosives.
- If ammonia and nitric acid react, the product is **ammonium nitrate**, which is used as a fertiliser and as an explosive.

Exercise: Summary Exercise

1. Look at the diagram and the descriptions of the nitrogen cycle earlier in the chapter:
   (a) Would you describe the changes that take place in the nitrogen cycle as *chemical* or *physical* changes? Explain your answer.
   (b) Are the changes that take place in the water cycle *physical* or *chemical* changes? Explain your answer.
2. Explain what is meant by each of the following terms:
   (a) nitrogen fixing
   (b) fertiliser
   (c) eutrophication
3. Explain why the fixing of atmospheric nitrogen is so important for the survival of life on earth.
4. Refer to the diagram below and then answer the questions that follow:



(a) Explain the role of *decomposers* in the nitrogen cycle.

(b) If the process taking place at (3) is *nitrification*, then label the processes at (1) and (5).

(c) Identify the nitrogen products at (2) and (4).

(d) On the diagram, indicate the type of *bacteria* that are involved in each stage of the nitrogen cycle.

(e) In industry, what process is used to produce the compound at 2?

(f) Does the diagram above show a 'cycle'? Explain your answer.

5. NO and NO_2 are both nitrogen compounds:

   (a) Explain how each of these compounds is formed?

   (b) What effect does each of these compounds have in the environment?

6. There are a number of arguments both 'for' and 'against' the use of artificial fertilisers. Draw a table to summarise the advantages and disadvantages of their use.

Chapter 20

The Hydrosphere - Grade 10

20.1 Introduction

As far as we know, the Earth we live on is the only planet that is able to support life. Among other things, Earth is just the right distance from the sun to have temperatures that are suitable for life to exist. Also, the Earth's atmosphere has exactly the right type of gases in the right amounts for life to survive. Our planet also has **water** on its surface, which is something very unique. In fact, Earth is often called the 'Blue Planet' because most of it is covered in water. This water is made up of *freshwater* in rivers and lakes, the *saltwater* of the oceans and estuaries, *groundwater* and *water vapour*. Together, all these water bodies are called the **hydrosphere**.

20.2 Interactions of the hydrosphere

It is important to realise that the hydrosphere interacts with other global systems, including the *atmosphere*, *lithosphere* and *biosphere*.

- *Atmosphere*

  When water is heated (e.g. by energy from the sun), it evaporates and forms water vapour. When water vapour cools again, it condenses to form liquid water which eventually returns to the surface by precipitation e.g. rain or snow. This cycle of water moving through the atmosphere, and the energy changes that accompany it, is what drives weather patterns on earth.

- *Lithosphere*

  In the lithosphere (the ocean and continental crust at the Earth's surface), water is an important *weathering* agent, which means that it helps to break rock down into rock fragments and then soil. These fragments may then be transported by water to another place, where they are deposited. This is called *erosion*. These two process i.e. weathering and erosion, help to shape the earth's surface. You can see this for example in rivers. In the upper streams, rocks are eroded and sediments are transported down the river and deposited on the wide flood plains lower down. On a bigger scale, river valleys in mountains have been carved out by the action of water, and cliffs and caves on rocky beach coastlines, are also the result of weathering and erosion by water.

- *Biosphere*

  In the biosphere, land plants absorb water through their roots and then transport this through their vascular (transport) system to stems and leaves. This water is needed in *photosynthesis*, the food production process in plants. Transpiration (evaporation of water from the leaf surface) then returns water back to the atmosphere.

20.3 Exploring the Hydrosphere

The large amount of water on our planet is something quite unique. In fact, about 71% of the earth is covered by water. Of this, almost 97% is found in the oceans as saltwater, about 2.2% occurs as a solid in ice sheets, while the remaining amount (less than 1%) is available as freshwater. So from a human perspective, despite the vast amount of water on the planet, only a very small amount is actually available for human consumption (e.g. drinking water). Before we go on to look more closely at the chemistry of the hydrosphere, we are going to spend some time exploring a part of the hydrosphere, in order to start appreciating what a complex and beautiful part of the world it is.

Activity :: Investigation : Investigating the hydrosphere

1. **Choosing a study site:**
   For this exercise, you can choose any part of the hydrosphere that you would like to explore. This may be a rock pool, a lake, river, wetland or even just a small pond. The guidelines below will apply best to a river investigation, but you can ask similar questions and gather similar data in other areas. When choosing your study site, consider how accessible it is (how easy is it to get to?) and the problems you may experience (e.g. tides, rain).
2. **Collecting data:**
   Your teacher will provide you with the equipment you need to collect the following data. You should have at least one study site where you will collect data, but you might decide to have more if you want to compare your results in different areas. This works best in a river, where you can choose sites down its length.
   (a) *Chemical data*
   Measure and record data such as temperature, pH, conductivity and dissolved oxygen at each of your sites. You may not know exactly what these measurements mean right now, but it will become clearer later in the chapter.
   (b) *Hydrological data*
   Measure the water velocity of the river and observe how the volume of water in the river changes as you move down its length. You can also collect a water sample in a clear bottle, hold it to the light and see whether the water is clear or whether it has particles in it.
   (c) *Biological data*
   What types of animals and plants are found in or near this part of the hydrosphere? Are they specially adapted to their environment?

   Record your data in a table like the one shown below:

	Site 1	**Site 2**	**Site 3**
Temperature			
pH			
Conductivity			
Dissolved oxygen			
Animals and plants			

3. **Interpreting the data:**
   Once you have collected and recorded your data, think about the following questions:
   - How does the data you have collected vary at different sites?
   - Can you explain these differences?
   - What effect do you think *temperature*, *dissolved oxygen* and *pH* have on animals and plants that are living in the hydrosphere?

- Water is seldom 'pure'. It usually has lots of things dissolved (e.g. Mg, Ca and NO_3^- ions) or suspended (e.g. soil particles, debris) in it. Where do these substances come from?
- Are there any human activities near this part of the hydrosphere? What effect could these activities have on the hydrosphere?

20.4 The Importance of the Hydrosphere

It is so easy sometimes to take our hydrosphere for granted, and we seldom take the time to really think about the role that this part of the planet plays in keeping us alive. Below are just some of the very important functions of water in the hydrosphere:

- *Water is a part of living cells*

  Each cell in a living organism is made up of almost 75% water, and this allows the cell to function normally. In fact, most of the chemical reactions that occur in life, involve substances that are dissolved in water. Without water, cells would not be able to carry out their normal functions, and life could not exist.

- *Water provides a habitat*

  The hydrosphere provides an important place for many animals and plants to live. Many gases (e.g. CO_2, O_2), nutrients e.g. nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) ions, as well as other ions (e.g. Ca^{2+} and Mg^{2+}) are dissolved in water. The presence of these substances is critical for life to exist in water.

- *Regulating climate*

  You may remember from chapter **??** that one of water's unique characteristics is its high *specific heat*. This means that water takes a long time to heat up, and also a long time to cool down. This is important in helping to regulate temperatures on earth so that they stay within a range that is acceptable for life to exist. *Ocean currents* also help to disperse heat.

- *Human needs*

  Humans use water in a number of ways. Drinking water is obviously very important, but water is also used domestically (e.g. washing and cleaning) and in industry. Water can also be used to generate electricity through hydropower.

These are just a few of the very important functions that water plays on our planet. Many of the functions of water relate to its chemistry and to the way in which it is able to dissolve substances in it.

20.5 Ions in aqueous solution

As we mentioned earlier, water is seldom pure. Because of the structure of the water molecule, it is able to dissolve substances in it. This is very important because if water wasn't able to do this, life would not be able to survive. In rivers and the oceans for example, dissolved oxygen means that organisms are still able to respire (breathe). For plants, dissolved nutrients are also available. In the human body, water is able to carry dissolved substances from one part of the body to another.

Many of the substances that dissolve are *ionic*, and when they dissolve they form ions in solution. We are going to look at how water is able to dissolve ionic compounds, and how these ions maintain a balance in the human body, how they affect water hardness, and how specific ions determine the pH of solutions.

20.5.1 Dissociation in water

You may remember from chapter 5 that water is a **polar molecule** (figure 20.1). This means that one part of the molecule has a slightly positive charge and the other part has a slightly negative charge.

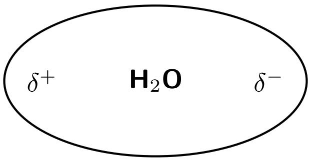


Figure 20.1: Water is a polar molecule

It is the polar nature of water that allows ionic compounds to dissolve in it. In the case of sodium chloride (NaCl) for example, the positive sodium ions (Na^+) will be attracted to the negative pole of the water molecule, while the negative chloride ions (Cl^-) will be attracted to the positive pole of the water molecule. In the process, the ionic bonds between the sodium and chloride ions are weakened and the water molecules are able to work their way between the individual ions, surrounding them and slowly dissolving the compound. This process is called **dissociation**. A simplified representation of this is shown in figure 20.2.

Definition: Dissociation
Dissociation in chemistry and biochemistry is a general process in which ionic compounds separate or split into smaller molecules or ions, usually in a reversible manner.

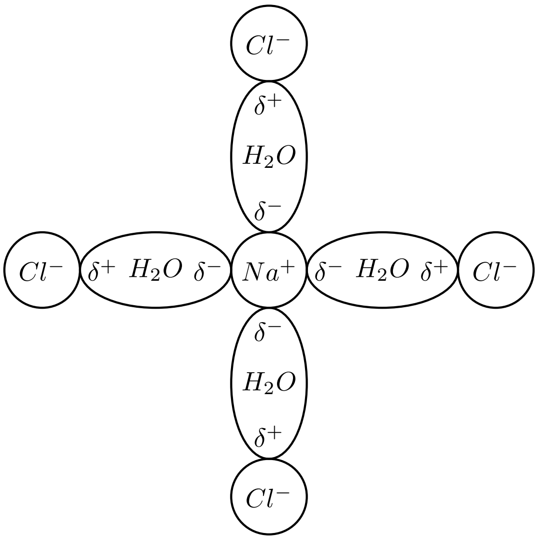


Figure 20.2: Sodium chloride dissolves in water

The dissolution of sodium chloride can be represented by the following equation:

$$NaCl(s) \rightarrow Na^+(aq) + Cl^-(aq)$$

The symbols **s** (solid), **l** (liquid), **g** (gas) and **aq** (material is dissolved in water) are written after the chemical formula to show the state or phase of the material. The dissolution of potassium sulphate into potassium and sulphate ions is shown below as another example:

$$K_2SO_4(s) \rightarrow 2K^+(aq) + SO_4^{2-}(aq)$$

Remember that **molecular** substances (e.g. covalent compounds) may also dissolve, but most will not form ions. One example is sugar.

$$C_6H_{12}O_6(s) \Leftrightarrow C_6H_{12}O_6(aq)$$

There are exceptions to this and some molecular substances *will* form ions when they dissolve. Hydrogen chloride for example can ionise to form hydrogen and chloride ions.

$$HCl(g) \rightarrow H^+(aq) + Cl^-(aq)$$

The ability of ionic compounds to dissolve in water is extremely important in the human body! The body is made up of *cells*, each of which is surrounded by a *membrane*. Dissolved ions are found inside and outside of body cells, in different concentrations. Some of these ions are positive (e.g. Mg^{2+}) and some are negative (e.g. Cl^-). If there is a difference in the charge that is inside and outside the cell, then there is a *potential difference* across the cell membrane. This is called the **membrane potential** of the cell. The membrane potential acts like a battery and affects the movement of all charged substances across the membrane. Membrane potentials play a role in muscle functioning, digestion, excretion and in maintaining blood pH, to name just a few. The movement of ions across the membrane can also be converted into an electric signal that can be transferred along *neurons* (nerve cells), which control body processes. If ionic substances were not able to dissociate in water, then none of these processes would be possible! It is also important to realise that our bodies can *lose* ions such as Na^+, K^+, Ca^{2+}, Mg^{2+}, and Cl^-, for example when we sweat during exercise. Sports drinks such as Lucozade and Powerade are designed to replace these lost ions so that the body's normal functioning is not affected.

Exercise: Ions in solution

1. For each of the following, say whether the substance is ionic or molecular.
   (a) potassium nitrate (KNO_3)
   (b) ethanol (C_2H_5OH)
   (c) sucrose sugar ($C_{12}H_{22}O_{11}$
   (d) sodium bromide ($NaBr$)
2. Write a balanced equation to show how each of the following ionic compounds dissociate in water.
   (a) sodium sulphate (Na_2SO_4)
   (b) potassium bromide (KBr)
   (c) potassium permanganate ($KMNO_4$)
   (d) sodium phosphate (Na_3PO_4)

20.5.2 Ions and water hardness

Definition: Water hardness
Water hardness is a measure of the mineral content of water. Minerals are substances such as calcite, quartz and mica that occur naturally as a result of geological processes.

Hard water is water that has a high mineral content. Water that has a low mineral content is known as **soft water**. If water has a high mineral content, it usually contains high levels of metal ions, mainly calcium (Ca) and magnesium (Mg). The calcium enters the water from either $CaCO_3$ (limestone or chalk) or from mineral deposits of $CaSO_4$. The main source of magnesium is a sedimentary rock called dolomite, $CaMg(CO_3)_2$. Hard water may also contain other metals as well as bicarbonates and sulphates.

The simplest way to check whether water is hard or soft is to use the lather/froth test. If the water is very soft, soap will lather more easily when it is rubbed against the skin. With hard water this won't happen. Toothpaste will also not froth well in hard water.

A **water softener** works on the principle of **ion exchange**. Hard water passes through a media bed, usually made of resin beads that are supersaturated with sodium. As the water passes through the beads, the hardness minerals (e.g. calcium and magnesium) attach themselves to the beads. The sodium that was originally on the beads is released into the water. When the resin becomes saturated with calcium and magnesium, it must be recharged. A salt solution is passed through the resin. The sodium replaces the calcium and magnesium, and these ions are released into the waste water and discharged.

20.5.3 The pH scale

The concentration of specific ions in solution, affects whether the solution is acidic or basic. You will learn about acids and bases in chapter 15. Acids and bases can be described as substances that either increase or decrease the concentration of hydrogen (H^+ or H_3O+) ions in a solution. An acid *increases* the hydrogen ion concentration in a solution, while a base *decreases* the hydrogen ion concentration. **pH** is used to measure whether a substance is acidic or basic (alkaline).

Definition: pH
pH is a measure of the acidity or alkalinity of a solution. The pH scale ranges from 0 to 14. Solutions with a pH less than seven are acidic, while those with a pH greater than seven are basic (alkaline). pH 7 is considered neutral.

pH can be calculated using the following equation:

$$pH = -log[H^+]$$

or

$$pH = -log[H_3O^+]$$

The brackets in the above equation are used to show *concentration* in mol.dm^{-3}.

Worked Example 93: pH calculations

Question: Calculate the pH of a solution where the concentration of hydrogen ions is 1×10^{-7} mol.dm^{-3}.

Answer

Step 1 : Determine the concentration of hydrogen ions in mol.dm^{-3}

In this example, the concentration has been given and is 1×10^{-7} mol.dm^{-3}

Step 2 : Substitute this value into the pH equation and calculate the pH value

pH = -log[H^+]
= -log(1×10^{-7})
= 7

Worked Example 94: pH calculations

Question: In a solution of ethanoic acid, the following equilibrium is established:

$$CH_3COOH(aq) + H_2O \Leftrightarrow CH_3COO^-(aq) + H_3O^+$$

The concentration of CH_3COO^- ions is found to be 0.003 mol.dm^{-3}. Calculate the pH of the solution.

Answer

Step 1 : Determine the concentration of hydrogen ions in the solution

According to the balanced equation for this reaction, the mole ratio of CH_3COO^- ions to H_3O^+ ions is the same, therefore the concentration of these two ions in the solution will also be the same. So, [H_3O^+] = 0.003 dm^{-3}.

Step 2 : Substitute this value into the pH equation and calculate the pH value

pH = -log[H_3O^+]
= -log(0.003)
= 2.52

Understanding pH is very important. In living organisms, it is necessary to maintain a constant pH so that chemical reactions can occur under optimal conditions.

Important: It may also be useful for calculations involving the pH scale, to know that the following equation can also be used:

$$[H_3O^+][OH^-] = 1 \times 10^{-14}$$

A build up of acid in the human body can be very dangerous. **Lactic acidosis** is a condition caused by the buildup of lactic acid in the body. It leads to acidification of the blood (acidosis) and can make a person very ill. Some of the symptoms of lactic acidosis are deep and rapid breathing, vomiting, and abdominal pain. In the fight against HIV, lactic acidosis is a problem. One of the antiretrovirals (ARV's) that is used in anti-HIV treatment is Stavudine (also known as Zerit or d4T). One of the side effects of Stavudine is lactic acidosis, particularly in overweight women. If it is not treated quickly, it can result in death.

In agriculture, farmers need to know the pH of their soils so that they are able to plant the right kinds of crops. The pH of soils can vary depending on a number of factors such as rainwater, the kinds of rocks and materials from which the soil was formed and also human influences such as pollution and fertilisers. The pH of rain water can also vary and this too has an effect on agriculture, buildings, water courses, animals and plants. Rainwater is naturally acidic because carbon dioxide in the atmosphere combines with water to form carbonic acid. Unpolluted rainwater has a pH of approximately 5.6. However, human activities can alter the acidity of rain and this can cause serious problems such as acid rain.

Exercise: Calculating pH

1. Calculate the pH of each of the following solutions:
   (a) A 0.2 mol.dm^{-3} KOH solution
   (b) A 0.5 mol.dm^{-3} HCl solution
2. What is the concentration (in mol.dm^{-3}) of H_3O^+ ions in a NaOH solution which has a pH of 12?
3. The concentrations of hydronium and hydroxyl ions in a typical sample of seawater are 10^{-8} mol.dm^{-3} and 10^{-6} mol.dm^{-3} respectively.
   (a) Is the seawater acidic or basic?
   (b) What is the pH of the seawater?
   (c) Give a possible explanation for the pH of the seawater.
   (IEB Paper 2, 2002)

20.5.4 Acid rain

The acidity of rainwater comes from the natural presence of three substances (CO_2, NO, and SO_2) in the lowest layer of the atmosphere. These gases are able to dissolve in water and therefore make rain more acidic than it would otherwise be. Of these gases, carbon dioxide (CO_2) has the highest concentration and therefore contributes the most to the natural acidity of rainwater. We will look at each of these gases in turn.

Definition: Acid rain
Acid rain refers to the deposition of acidic components in rain, snow and dew. Acid rain occurs when sulfur dioxide and nitrogen oxides are emitted into the atmosphere, undergo chemical transformations, and are absorbed by water droplets in clouds. The droplets then fall to earth as rain, snow, mist, dry dust, hail, or sleet. This increases the acidity of the soil, and affects the chemical balance of lakes and streams.

1. **Carbon dioxide**

   Carbon dioxide reacts with water in the atmosphere to form **carbonic acid** (H_2CO_3).

   $$CO_2 + H_2O \rightarrow H_2CO_3$$

   The carbonic acid dissociates to form hydrogen and hydrogen carbonate ions. It is the presence of hydrogen ions that lowers the pH of the solution, making the rain acidic.

   $$H_2CO_3 \rightarrow H^+ + HCO_3^-$$

2. **Nitric oxide**

   Nitric oxide (NO) also contributes to the natural acidity of rainwater and is formed during lightning storms when nitrogen and oxygen react. In air, NO is oxidised to form nitrogen dioxide (NO_2). It is the nitrogen dioxide which then reacts with water in the atmosphere to form **nitric acid** (HNO_3).

   $$3NO_2(g) + H_2O \rightarrow 2HNO_3(aq) + NO(g)$$

   The nitric acid dissociates in water to produce hydrogen ions and nitrate ions. This again lowers the pH of the solution, making it acidic.

   $$HNO_3 \rightarrow H^+ + NO_3^-$$

3. **Sulfur dioxide**

   Sulfur dioxide in the atmosphere first reacts with oxygen to form sulfur trioxide, before reacting with water to form **sulfuric acid**.

   $$2SO_2 + O_2 \rightarrow 2SO_3$$

   $$SO_3 + H_2O \rightarrow H_2SO_4$$

   Sulfuric acid dissociates in a similar way to the previous reactions.

   $$H_2SO_4 \rightarrow HSO_4^- + H^+$$

Although these reactions do take place naturally, human activities can greatly increase the concentration of these gases in the atmosphere, so that rain becomes far more acidic than it would otherwise be. The burning of fossil fuels in industries, vehicles etc is one of the biggest culprits. If the acidity of the rain drops below 5, it is referred to as **acid rain**.

Acid rain can have a very damaging effect on the environment. In rivers, dams and lakes, increased acidity can mean that some species of animals and plants will not survive. Acid rain can also degrade soil minerals, producing metal ions that are washed into water systems. Some of these ions may be toxic e.g. Al^{3+}. From an economic perspective, altered soil pH can drastically affect agricultural productivity.

Acid rain can also affect buildings and monuments, many of which are made from marble and limestone. A chemical reaction takes place between $CaCO_3$ (limestone) and sulfuric acid to produce aqueous ions which can be easily washed away. The same reaction can occur in the lithosphere where limestone rocks are present e.g. limestone caves can be eroded by acidic rainwater.

$$H_2SO_4 + CaCO_3 \rightarrow CaSO_4.H_2O + CO_2$$

Activity :: Investigation : Acid rain

You are going to test the effect of 'acid rain' on a number of substances.

Materials needed:

samples of chalk, marble, zinc, iron, lead, dilute sulfuric acid, test tubes, beaker, glass dropper

Method:

1. Place a small sample of each of the following substances in a separate test tube: chalk, marble, zinc, iron and lead
2. To each test tube, add a few drops of dilute sulfuric acid.
3. Observe what happens and record your results.

Discussion questions:

- In which of the test tubes did reactions take place? What happened to the sample substances?
- What do your results tell you about the effect that acid rain could have on each of the following: buildings, soils, rocks and geology, water ecosystems?
- What precautions could be taken to reduce the potential impact of acid rain?

20.6 Electrolytes, ionisation and conductivity

Conductivity in aqueous solutions, is a measure of the ability of water to conduct an electric current. The more **ions** there are in the solution, the higher its conductivity.

Definition: Conductivity
Conductivity is a measure of a solution's ability to conduct an electric current.

20.6.1 Electrolytes

An **electrolyte** is a material that *increases* the conductivity of water when dissolved in it. Electrolytes can be further divided into **strong electrolytes** and **weak electrolytes**.

Definition: Electrolyte
An electrolyte is a substance that contains free ions and behaves as an electrically conductive medium. Because they generally consist of ions in solution, electrolytes are also known as ionic solutions.

1. **Strong electrolytes**

   A strong electrolyte is a material that ionises completely when it is dissolved in water:

   $$AB(s,l,g) \rightarrow A^{+}(aq) + B^{-}(aq)$$

   This is a **chemical change** because the original compound has been split into its component ions and bonds have been broken. In a strong electrolyte, we say that the *extent of ionisation* is high. In other words, the original material dissociates completely so that there is a high concentration of ions in the solution. An example is a solution of potassium nitrate:

   $$KNO_3(s) \rightarrow K^{+}(aq) + NO_3^{-}(aq)$$

2. **Weak electrolytes**

   A weak electrolyte is a material that goes into solution and will be surrounded by water molecules when it is added to water. However, not *all* of the molecules will dissociate into ions. The *extent of ionisation* of a weak electrolyte is low and therefore the concentration of ions in the solution is also low.

   $$AB(s,l,g) \rightarrow AB(aq) \Leftrightarrow A^{+}(aq) + B^{-}(aq)$$

   The following example shows that, in the final solution of a weak electrolyte, some of the original compound *plus* some dissolved ions are present.

   $$C_2H_3O_2H(l) \rightarrow C_2H_3O_2H \Leftrightarrow C_2H_3O_2^{-}(aq) + H^{+}(aq)$$

20.6.2 Non-electrolytes

A **non-electrolyte** is a material that does not increase the conductivity of water when dissolved in it. The substance goes into solution and becomes surrounded by water molecules, so that the molecules of the chemical become separated from each other. However, although the substance does dissolve, it is not changed in any way and no chemical bonds are broken. The change is a **physical change**. In the oxygen example below, the reaction is shown to be reversible because oxygen is only partially soluble in water and comes out of solution very easily.

$$C_2H_5OH(l) \rightarrow C_2H_5OH(aq)$$

$$O_2(g) \Leftrightarrow O_2(aq)$$

20.6.3 Factors that affect the conductivity of water

The conductivity of water is therefore affected by the following factors:

- The **type of substance** that dissolves in water

  Whether a material is a strong electrolyte (e.g. potassium nitrate, KNO_3), a weak electrolyte (e.g. acetate, $C_2H_3O_2H$) or a non-electrolyte (e.g. sugar, alcohol, oil) will affect the conductivity of water because the concentration of ions in solution will be different in each case.

- The **concentration of ions** in solution

  The higher the concentration of ions in solution, the higher its conductivity will be.

- **Temperature**

  The warmer the solution the higher the solubility of the material being dissolved, and therefore the higher the conductivity as well.

Activity :: Experiment : Electrical conductivity

Aim:

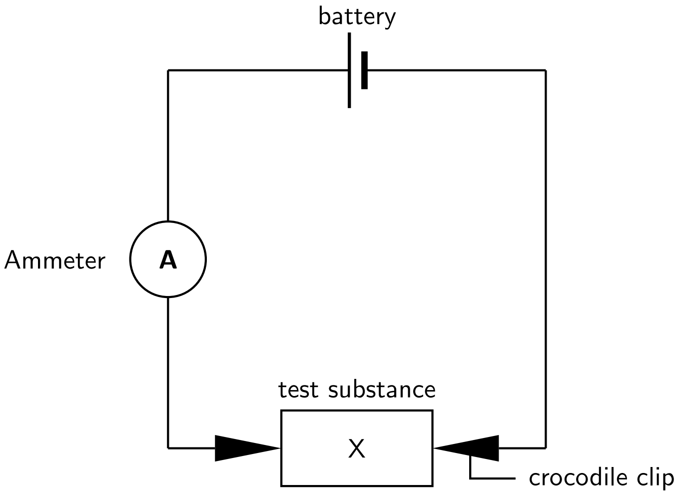
To investigate the electrical conductivities of different substances and solutions.

Apparatus:

solid salt (NaCl) crystals; different liquids such as distilled water, tap water, seawater, benzene and alcohol; solutions of salts e.g. NaCl, KBr; a solution of an acid (e.g. HCl) and a solution of a base (e.g. NaOH); torch cells; ammeter; conducting wire, crocodile clips and 2 carbon rods.

Method:

Set up the experiment by connecting the circuit as shown in the diagram below. In the diagram, 'X' represents the substance or solution that you will be testing. When you are using the solid crystals, the crocodile clips can be attached directly to each end of the crystal. When you are using solutions, two carbon rods are placed into the liquid, and the clips are attached to each of the rods. In each case, complete the circuit and allow the current to flow for about 30 seconds. Observe whether the ammeter shows a reading.



Results:

Record your observations in a table similar to the one below:

Test substance	Ammeter reading

What do you notice? Can you explain these observations?

Remember that for electricity to flow, there needs to be a movement of charged particles e.g. ions. With the solid NaCl crystals, there was no flow of electricity recorded on the ammeter. Although the solid is made up of ions, they are held together very tightly within the crystal lattice, and therefore no current will flow. Distilled water, benzene and alcohol also don't conduct a current because they are *covalent compounds* and therefore do not contain ions.

The ammeter should have recorded a current when the salt solutions and the acid and base solutions were connected in the circuit. In solution, salts *dissociate* into their ions, so that these are free to move in the solution. Acids and bases behave in a similar way, and dissociate to form hydronium and oxonium ions. Look at the following examples:

$$\mathrm{KBr} \rightarrow \mathrm{K}^+ + \mathrm{Br}^-$$
$$\mathrm{NaCl} \rightarrow \mathrm{Na}^+ + \mathrm{Cl}^-$$
$$\mathrm{HCl} + \mathrm{H_2O} \rightarrow \mathrm{H_3O}^+ + \mathrm{Cl}^-$$
$$\mathrm{NaOH} \rightarrow \mathrm{Na}^+ + \mathrm{OH}^-$$

Conclusions:

Solutions that contain free-moving ions are able to conduct electricity because of the movement of charged particles. Solutions that do not contain free-moving ions do not conduct electricity.

Conductivity in streams and rivers is affected by the geology of the area where the water is flowing through. Streams that run through areas with granite bedrock tend to have lower conductivity because granite is made of materials that do not ionise when washed into the water. On the other hand, streams that run through areas with clay soils tend to have higher conductivity because the materials ionise when they are washed into the water. Pollution can also affect conductivity. A failing sewage system or an inflow of fertiliser runoff would raise the conductivity because of the presence of chloride, phosphate, and nitrate (ions) while an oil spill (non-ionic) would lower the conductivity. It is very important that conductivity is kept within a certain acceptable range so that the organisms living in these water systems are able to survive.

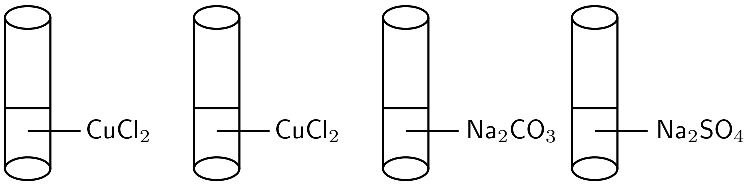
20.7 Precipitation reactions

Sometimes, ions in solution may react with each other to form a new substance that is *insoluble*. This is called a **precipitate**.

Definition: Precipitate
A precipitate is the solid that forms in a solution during a chemical reaction.

Activity :: Demonstration : The reaction of ions in solution
Apparatus and materials:

4 test tubes; copper(II) chloride solution; sodium carbonate solution; sodium sulphate solution



Method:

1. Prepare 2 test tubes with approximately 5 ml of dilute Cu(II)chloride solution in each
2. Prepare 1 test tube with 5 ml sodium carbonate solution
3. Prepare 1 test tube with 5 ml sodium sulphate solution
4. Carefully pour the sodium carbonate solution into one of the test tubes containing copper(II) chloride and observe what happens
5. Carefully pour the sodium sulphate solution into the second test tube containing copper(II) chloride and observe what happens

Results:

1. A light blue precipitate forms when sodium carbonate reacts with copper(II) chloride
2. No precipitate forms when sodium sulphate reacts with copper(II) chloride

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It is important to understand what happened in the previous demonstration. We will look at what happens in each reaction, step by step.

1. **Reaction 1:** Sodium carbonate reacts with copper(II) chloride

   When these compounds react, a number of ions are present in solution: Cu^{2+}, Cl^-, Na^+ and CO_3^{2-}.

   Because there are lots of ions in solution, they will collide with each other and may recombine in different ways. The product that forms may be insoluble, in which case a precipitate will form, or the product will be soluble, in which case the ions will go back into solution. Let's see how the ions in this example could have combined with each other:

   $\mathrm{Cu^{2+} + CO_3^{2-} \rightarrow CuCO_3}$

   $\mathrm{Cu^{2+} + 2Cl^- \rightarrow CuCl_2}$

   $\mathrm{Na^+ + Cl^- \rightarrow NaCl}$

   $\mathrm{Na^+ + CO_3^{2-} \rightarrow Na_2CO_3}$

   You can automatically exclude the reactions where sodium carbonate and copper(II) chloride are the products because these were the initial reactants. You also know that sodium chloride (NaCl) is soluble in water, so the remaining product (copper carbonate) must be the one that is insoluble. It is also possible to look up which salts are soluble and which are insoluble. If you do this, you will find that most carbonates are insoluble, therefore the precipitate that forms in this reaction must be $CuCO_3$. The reaction that has taken place between the ions in solution is as follows:

   $$2Na^+ + CO_3^{2-} + Cu^{2+} + 2Cl^- \rightarrow CuCO_3 + 2Na^+ + 2Cl^-$$

2. **Reaction 2:** Sodium sulphate reacts with copper(II) chloride

   The ions that are present in solution are Cu^{2+}, Cl^-, Na^+ and SO_4^{2-}.

   The ions collide with each other and may recombine in different ways. The possible combinations of the ions are as follows:

   $\mathrm{Cu^{2+} + SO_4^{2-} \rightarrow CuSO_4}$

   $\mathrm{Cu^{2+} + 2Cl^- \rightarrow CuCl_2}$

   $\mathrm{Na^+ + Cl^- \rightarrow NaCl}$

   $\mathrm{Na^+ + SO_4^{2-} \rightarrow Na_2SO_4}$

   If we look up which of these salts are soluble and which are insoluble, we see that most chlorides and most sulphates are soluble. This is why no precipitate forms in this second reaction. Even when the ions recombine, they immediately separate and go back into solution. The reaction that has taken place between the ions in solution is as follows:

   $$2Na^+ + SO_4^{2-} + Cu^{2+} + 2Cl^- \rightarrow 2Na^+ + SO_4^{2-} + Cu^{2+} + 2Cl^-$$

Table 20.1 shows some of the general rules about the solubility of different salts based on a number of investigations:

Table 20.1: General rules for the solubility of salts

Salt	**Solubility**
Nitrates	All are soluble
Potassium, sodium and ammonium salts	All are soluble
Chlorides	All are soluble except silver chloride, lead(II)chloride and mercury(II)chloride
Sulphates	All are soluble except lead(II)sulphate, barium sulphate and calcium sulphate
Carbonates	All are insoluble except those of potassium, sodium and ammonium

20.8 Testing for common anions in solution

It is also possible to carry out tests to determine which ions are present in a solution.

20.8.1 Test for a chloride

Prepare a solution of the unknown salt using distilled water and add a small amount of **silver nitrate** solution. If a white precipitate forms, the salt is either a chloride or a carbonate.

$$\mathrm{Cl^- + Ag^+ + NO_3^- \rightarrow AgCl + NO_3^-} \text{ (AgCl is white precipitate)}$$

$$\mathrm{CO_3^{2-} + 2Ag^+ + 2NO_3^- \rightarrow Ag_2CO_3 + 2NO_2} \text{ (Ag}_2\text{CO}_3\text{ is white precipitate)}$$

The next step is to treat the precipitate with a small amount of **concentrated nitric acid**. If the precipitate remains unchanged, then the salt is a chloride. If carbon dioxide is formed, and the precipitate disappears, the salt is a carbonate.

$$\mathrm{AgCl + HNO_3 \rightarrow} \text{ (no reaction; precipitate is unchanged)}$$

$$\mathrm{Ag_2CO_3 + 2HNO_3 \rightarrow 2AgNO_3 + H_2O + CO_2} \text{ (precipitate disappears)}$$

20.8.2 Test for a sulphate

Add a small amount of barium chloride solution to a solution of the test salt. If a white precipitate forms, the salt is either a sulphate or a carbonate.

$$\mathrm{SO_4^{2-} + Ba^{2+} + Cl^- \rightarrow BaSO_4 + Cl^-} \text{ (BaSO}_4\text{ is a white precipitate)}$$

$$\mathrm{CO_3^{2-} + Ba^{2+} + Cl^- \rightarrow BaCO_3 + Cl^-} \text{ (BaCO}_3\text{ is a white precipitate)}$$

If the precipitate is treated with nitric acid, it is possible to distinguish whether the salt is a sulphate or a carbonate (as in the test for a chloride).

$$\mathrm{BaSO_4 + HNO_3 \rightarrow} \text{ (no reaction; precipitate is unchanged)}$$

$$\mathrm{BaCO_3 + 2HNO_3 \rightarrow Ba(NO_3)_2 + H_2O + CO_2} \text{ (precipitate disappears)}$$

20.8.3 Test for a carbonate

If a sample of the dry salt is treated with a small amount of acid, the production of carbon dioxide is a positive test for a carbonate.

$$\text{Acid} + CO_3^{2-} \rightarrow CO_2$$

If the gas is passed through limewater and the solution becomes milky, the gas is carbon dioxide.

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \text{ (It is the insoluble CaCO}_3\text{ precipitate that makes the limewater go milky)}$$

20.8.4 Test for bromides and iodides

As was the case with the chlorides, the bromides and iodides also form precipitates when they are reacted with silver nitrate. Silver chloride is a white precipitate, but the silver bromide and silver iodide precipitates are both pale yellow. To determine whether the precipitate is a bromide or an iodide, we use chlorine water and carbon tetrachloride (CCl_4).

Chlorine water frees bromine gas from the bromide, and colours the carbon tetrachloride a reddish brown.

Chlorine water frees iodine gas from an iodide, and colours the carbon tetrachloride is coloured purple.

Exercise: Precipitation reactions and ions in solution

1. Silver nitrate ($AgNO_3$) reacts with potassium chloride (KCl) and a white precipitate is formed.
   (a) Write a balanced equation for the reaction that takes place.
   (b) What is the name of the insoluble salt that forms?
   (c) Which of the salts in this reaction are soluble?
2. Barium chloride reacts with sulfuric acid to produce barium sulphate and hydrochloric acid.
   (a) Write a balanced equation for the reaction that takes place.
   (b) Does a precipitate form during the reaction?
   (c) Describe a test that could be used to test for the presence of barium sulphate in the products.
3. A test tube contains a clear, colourless salt solution. A few drops of silver nitrate solution are added to the solution and a pale yellow precipitate forms. Which one of the following salts was dissolved in the original solution?
   (a) NaI
   (b) KCl
   (c) K_2CO_3
   (d) Na_2SO_4

   (IEB Paper 2, 2005)

20.9 Threats to the Hydrosphere

It should be clear by now that the hydrosphere plays an extremely important role in the survival of life on Earth, and that the unique properties of water allow various important chemical processes to take place which would otherwise not be possible. Unfortunately for us however, there are a number of factors that threaten our hydrosphere, and most of these threats are because of human activities. We are going to focus on two of these issues: **overuse** and **pollution** and look at ways in which these problems can possibly be overcome.

1. **Overuse of water**

   We mentioned earlier that only a very small percentage of the hydrosphere's water is available as freshwater. However, despite this, humans continue to use more and more water to the point where water *consumption* is fast approaching the amount of water that is *available*. The situation is a serious one, particularly in countries such as South Africa which are naturally dry, and where water resources are limited. It is estimated that between 2020 and 2040, water supplies in South Africa will no longer be able to meet the growing demand for water in this country. This is partly due to population growth, but also because of the increasing needs of industries as they expand and develop. For each of us, this should be a very scary thought. Try to imagine a day without water...difficult isn't it? Water is so much a part of our lives, that we are hardly aware of the huge part that it plays in our daily lives.

Activity :: Discussion : Creative water conservation

As populations grow, so do the demands that are placed on dwindling water resources. While many people argue that building dams helps to solve this water-shortage problem, the reality is that dams are only a temporary solution, and that they often end up doing far more ecological damage than good. The only sustainable solution is to reduce the *demand* for water, so that water supplies are sufficient to meet this. The more important question then is how to do this.

Discussion:

Divide the class into groups, so that there are about five people in each. Each group is going to represent a different sector within society. Your teacher will tell you which sector you belong to from the following: Farming, industry, city management or civil society (i.e. you will represent the ordinary 'man on the street'). In your groups, discuss the following questions as they relate to the group of people you represent: (Remember to take notes during your discussions, and nominate a spokesperson to give feedback to the rest of the class on behalf of your group)

- What steps could be taken by your group to conserve water?
- Why do you think these steps are *not* being taken?
- What incentives do you think could be introduced to encourage this group to conserve water more efficiently?

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2. **Pollution**

   Pollution of the hydrosphere is also a major problem. When we think of pollution, we sometimes only think of things like plastic, bottles, oil and so on. But any chemical that is present in the hydrosphere in an amount that is not what it should be is a pollutant. Animals and plants that live in the hydrosphere are specially adapted to surviving within a certain range of conditions. If these conditions are changed (e.g. through pollution), these organisms may not be able to survive. Pollution then, can affect entire aquatic ecosystems. The most common forms of pollution in the hydrosphere are *waste products* from humans and from industries, *nutrient pollution* e.g. fertiliser runoff which causes eutrophication (this will be discussed in a later section) and toxic trace elements such as aluminium, mercury and copper to name a few. Most of these elements come from mines or from industries.

It is important to realise that our hydrosphere exists in a delicate balance with other systems, and that disturbing this balance can have serious consequences for life on this planet.

Activity :: Group Project : School Action Project
There is a lot that can be done within a school to save water. As a class, discuss what actions could be taken by your class to make people more aware of how important it is to conserve water.

20.10 Summary

- The **hydrosphere** includes all the water that is on Earth. Sources of water include freshwater (e.g. rivers, lakes), saltwater (e.g. oceans), groundwater (e.g. boreholes) and water vapour. Ice (e.g. glaciers) is also part of the hydrosphere.
- The hydrosphere interacts with other **global systems**, including the atmosphere, lithosphere and biosphere.
- The hydrosphere has a number of important **functions**. Water is a part of all living cells, it provides a habitat for many living organisms, it helps to regulate climate, and it is used by humans for domestic, industrial and other use.
- The **polar** nature of water means that **ionic compounds** dissociate easily in aqueous solution into their component ions.
- **Ions** in solution play a number of roles. In the human body for example, ions help to regulate the internal environment (e.g. controlling muscle function, regulating blood pH). Ions in solution also determine water hardness and pH.
- **Water hardness** is a measure of the mineral content of water. Hard water has a high mineral concentration and generally also a high concentration of metal ions e.g. calcium and magnesium. The opposite is true for soft water.
- **pH** is a measure of the concentration of hydrogen ions in solution. The formula used to calculate pH is as follows:

  $$\text{pH} = \text{-log}[H_3O^+] \text{ or } \text{pH} = \text{-log}[H^+]$$

  A solution with a pH less than 7 is considered acidic and more than 7 is considered basic (or alkaline). A neutral solution has a pH of 7.
- Gases such as CO_2, NO_2 and SO^2 dissolve in water to form weak acid solutions. Rain is naturally acidic because of the high concentrations of carbon dioxide in the atmosphere. Human activities such as burning fossil fuels, increase the concentration of these gases in the atmosphere, resulting in **acid rain**.
- **Conductivity** is a measure of a solution's ability to conduct an electric current.
- An **electrolyte** is a substance that contains free ions, and is therefore able to conduct an electric current. Electrolytes can be divided into **strong** and **weak** electrolytes, based on the extent to which the substance ionises in solution.
- A **non-electrolyte** cannot conduct an electric current because it dooes not contain free ions.
- The **type of substance**, the **concentration of ions** and the **temperature** of the solution, affect its conductivity.

- A **precipitate** is formed when ions in solution react with each other to form an insoluble product. Solubility 'rules' help to identify the precipitate that has been formed.
- A number of tests can be used to identify whether certain **anions** are present in a solution.
- Despite the importance of the hydrosphere, a number of factors threaten it. These include **overuse** of water, and **pollution**.

Exercise: Summary Exercise

1. Give one word for each of the following descriptions:
   (a) the change in phase of water from a gas to a liquid
   (b) a charged atom
   (c) a term used to describe the mineral content of water
   (d) a gas that forms sulfuric acid when it reacts with water
2. Match the information in column A with the information in column B by writing only the letter (A to I) next to the question number (1 to 7)

Column A	Column B
1. A polar molecule	A. H_2SO_4
2. molecular solution	B. $CaCO_3$
3. Mineral that increases water hardness	C. NaOH
4. Substance that increases the hydrogen ion concentration	D. salt water
5. A strong electrolyte	E. calcium
6. A white precipitate	F. carbon dioxide
7. A non-conductor of electricity	G. potassium nitrate
	H. sugar water
	I. O_2

3. For each of the following questions, choose the one correct answer from the list provided.
   (a) Which one of the following substances does not conduct electricity in the solid phase but is an electrical conductor when molten?
      i. Cu
      ii. $PbBr_2$
      iii. H_2O
      iv. I_2
      (IEB Paper 2, 2003)
   (b) The following substances are dissolved in water. Which one of the solutions is basic?
      i. sodium nitrate
      ii. calcium sulphate
      iii. ammonium chloride
      iv. potassium carbonate
      (IEB Paper 2, 2005)
4. The concentration of hydronium and hydroxyl ions in a typical sample of seawater are 10^{-8} and 10^{-6} respectively.
   (a) Is the seawater acidic or basic?
   (b) Calculate the pH of this seawater.
5. Three test tubes (X, Y and Z) each contain a solution of an unknown potassium salt. The following observations were made during a practical investigation to identify the solutions in the test tubes:
   A: A white precipitate formed when silver nitrate ($AgNO_3$) was added to test tube Z.

B: A white precipitate formed in test tubes X and Y when barium chloride ($BaCl_2$) was added.

C: The precipitate in test tube X dissolved in hydrochloric acid (HCl) and a gas was released.

D: The precipitate in test tube Y was insoluble in hydrochloric acid.

(a) Use the above information to identify the solutions in each of the test tubes X, Y and Z.

(b) Write a chemical equation for the reaction that took place in test tube X before hydrochloric acid was added.

(DoE Exemplar Paper 2 2007)

Chapter 21

The Lithosphere - Grade 11

(NOTE TO SELF: Need map showing major mining areas in SA)

21.1 Introduction

If we were to cut the Earth in half we would see that our planet is made up of a number of layers, namely the **core** at the centre, the **mantle** and the outer **crust** (figure 21.1). The core is made up mostly of iron. The mantle, which lies between the core and the crust, consists of molten rock, called **magma** which moves continuously because of convection currents. The crust is the thin, hard outer layer that 'floats' on the magma of the mantle. It is the upper part of the mantle and the crust that make up the **lithosphere** ('lith' means 'types of stone' and 'sphere' refers to the round shape of the earth). Together, the lithosphere, hydrosphere and atmosphere make up the world as we know it.

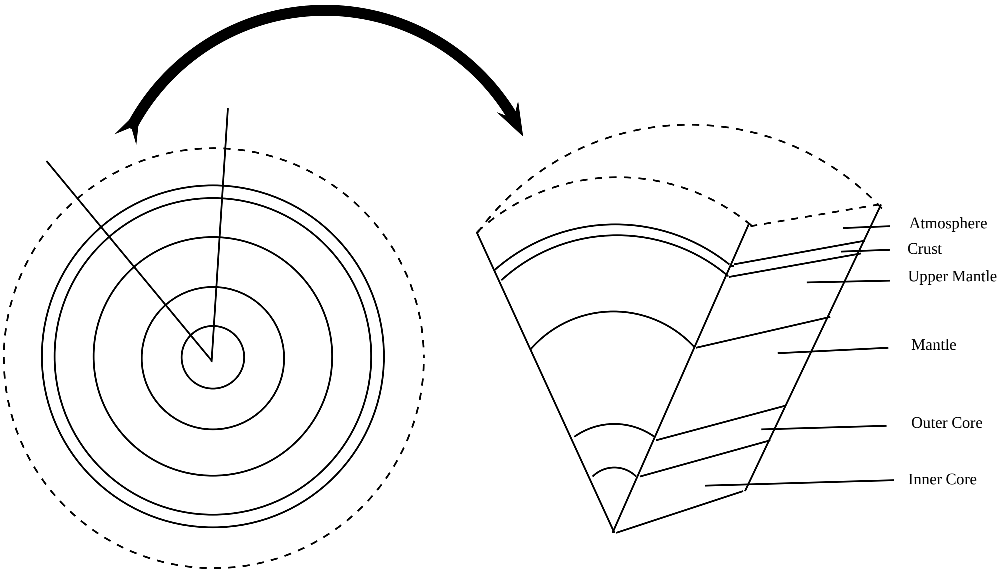


Figure 21.1: A cross-section through the earth to show its different layers

Definition: Lithosphere
The lithosphere is the solid outermost shell of our planet. The lithosphere includes the crust and the upper part of the mantle, and is made up of material from both the continents and the oceans on the Earth's surface.

Earlier chapters have focused on the hydrosphere (chapter 20) and the atmosphere (chapter 22). The lithosphere is also very important, not only because it is the surface on which we live, but also because humans gain many valuable resources from this part of the planet.

21.2 The chemistry of the earth's crust

The crust is made up of about 80 elements, which occur in over 2000 different compounds and minerals. However, most of the mass of crustal material is made up of only 8 of these elements. These are oxygen (O), silica (Si), aluminium (Al), iron (Fe), calcium (Ca), sodium (Na), potassium (K) and magnesium (Mg). These metal elements are seldom found in their pure form, but are usually part of other more complex **minerals**. A mineral is a compound that is formed through geological processes, which give it a particular structure. A mineral could be a pure element, but more often minerals are made up of many different elements combined. *Quartz* is just one example. It is a mineral that is made up of silica and oxygen. Some more examples are shown in table 21.1.

Definition: Mineral
Minerals are natural compounds formed through geological processes. The term 'mineral' includes both the material's chemical composition and its structure. Minerals range in composition from pure elements to complex compounds.

Table 21.1: Table showing examples of minerals and their chemistry

Mineral	**Chemistry**	**Comments**
Quartz	SiO_2 (silicon dioxide)	Quartz is used for glass, in electrical components, optical lenses and in building stone
Gold	Au (pure element) or $AuTe_2$ (Calaverite, a gold mineral)	Gold is often found in a group of minerals called the *tellurides*. Calaverite is a mineral that belongs to this group, and is the most common gold-bearing mineral. Gold has an affinity for tellurium (Te).
Hematite	Fe_2O_3 (iron oxide)	Iron usually occurs in iron oxide minerals or as an alloy of iron and nickel.
Orthoclase	$KAlSi_3O_8$ (potassium aluminium silicate)	Orthoclase belongs to the *feldspar* group of minerals.
Copper	Cu (pure element) or $Cu_2(CO_3)(OH)_2$ (malachite or copper carbonate hydroxide)	copper can be mined as a pure element or as a mineral such as malachite.

A **rock** is a combination of one or more minerals. *Granite* for example, is a rock that is made up of minerals such as SiO_2, Al_2O_3, CaO, K_2O, Na_2O and others. There are three different types of rocks, **igneous**, **sedimentary** and **metamorphic**. Igneous rocks (e.g. granite, basalt) are formed when magma is brought to the earth's surface as lava, and then solidifies. Sedimentary rocks (e.g. sandstone, limestone) form when rock fragments, organic matter or other sediment particles are deposited and then compacted over time until they solidify. Metamorphic rock is formed when any other rock types are subjected to intense heat and pressure over a period of time. Examples include slate and marble.

Many of the elements that are of interest to us (e.g. gold, iron, copper), are unevenly distributed in the lithosphere. In places where these elements are abundant, it is profitable to extract them (e.g. through mining) for economic purposes. If their concentration is very low, then the cost of extraction becomes more than the money that would be made if they were sold. Rocks that contain valuable minerals are called **ores**. As humans, we are particularly interested in the ores that contain metal elements, and also in those minerals that can be used to produce energy.

Definition: Ore
An ore is a volume of rock that contains minerals which make it valuable for mining.

A **gemstone** (also sometimes called a **gem** or **semi-precious stone**), is a highly attractive and valuable piece of mineral which, when cut and polished, is used in jewelry and other adornments. Examples of gemstones are amethyst, diamond, cat's eye and sapphire.

Exercise: Rocks and minerals

1. Where are most of the earth's minerals concentrated?
2. Explain the difference between a *mineral*, a *rock* and an *ore*.
3. Carry out your own research to find out which elements are found in the following minerals:
    (a) gypsum
    (b) calcite
    (c) topaz
4. Which minerals are found in the following rocks?
    (a) basalt
    (b) sandstone
    (c) marble

21.3 A brief history of mineral use

Many of the minerals that are important to humans are **metals** such as gold, aluminium, copper and iron. Throughout history, metals have played a very important role in making jewelery, tools, weapons and later machinery and other forms of technology. We have become so used to having metals around us that we seldom stop to think what life might have been like before metals were discovered. During the **Stone Age** for example, **stones** were used to make tools. Slivers of stone were cut from a rock and then sharpened. In Africa, some of the stone tools that have been found date back to 2.5 million years ago!

It was the discovery of *metals* that led to some huge advances in agriculture, warfare, transport and even cookery. One of the first metals to be discovered was **gold**, probably because of its beautiful shiny appearance. Gold was used mostly to make jewelery because it was too soft to make harder tools. Later, **copper** became an important metal because it could be hammered into shape, and it also lasted a lot longer than the stone that had previously been used in knives, cooking utensils and weapons. Copper can also be melted and then put into a mould to re-shape it. This is known as **casting**.

At about the time that copper was in widespread use, it was discovered that if certain kinds of stones are heated to high enough temperatures, liquid metals flow from them. These rocks are

ores, and contain the metal minerals inside them. The process of heating mineral ores in this way is called **smelting**. It was also found that ores do not only occur at the earth's surface, but also deep *below* it. This discovery led to the beginning of **mining**.

But humans' explorations into the world of metals did not end here! In some areas, the ores of *iron* and *tin* were found close together. The cast alloy of these two metals is **bronze**. Bronze is a very useful metal because it produces a sharper edge than copper. Another important discovery was that of **iron**. Iron is the most abundant metal at the earth's surface but it is more difficult to work with than copper or tin. It is very difficult to extract iron from its ore because it has an extremely high melting point, and only specially designed furnaces are able to produce the temperatures that are needed. An important discovery was that if iron is heated in a furnace with *charcoal*, some of the carbon in the charcoal is transferred to the iron, making the metal even harder. If this hot metal has its temperature reduced very suddenly, it becomes even harder and produces **steel**. Today, steel is a very important part of industry and construction.

Originally it was believed that much of Africa's knowledge of metals and their uses was from the Middle East. But this may not be the case. More recent studies have shown that iron was used far earlier than it would have been if knowledge of this metal had started in the Middle East. Many metal technologies may in fact have developed independently in Africa and in many African countries, metals have an extremely important place in society. In Nigeria's Yoruba country for example, iron has divine status because it is used to make instruments for survival. 'Ogun', the God of Iron, is seen as the protector of the kingdom.

21.4 Energy resources and their uses

Apart from minerals and ores, the products of the lithosphere are also important in meeting our energy needs.

Coal is one of the most important fuels that is used in the production of electricity. Coal is formed from organic material when plants and animals decompose, leaving behind organic remains that accumulate and become compacted over millions of years under sedimentary rock. The layers of compact organic material that can be found between sedimentary layers, are coal. When coal is burned, a large amount of heat energy is released, which is used to produce electricity. South Africa is the world's sixth largest coal producer, with Mpumalanga contributing about 83

Another element that is found in the crust, and which helps to meet our energy needs, is **uranium**. Uranium produces energy through the process of *nuclear fission*. Neutrons are aimed at the nucleii of the uranium atoms in order to split them. When the nucleus of a uranium atom is split, a large amount of energy is released as heat. This heat is used to produce steam, which turns turbines to generate electricity. Uranium is produced as a by-product of gold in some mines in the Witwatersrand, and as a by-product in some copper mines, for example in Phalaborwa. This type of nuclear power is relatively environmentally friendly since it produces low gas emissions. However, the process does produce small amounts of radioactive wastes , which must be carefully disposed of in order to prevent contamination.

Oil is another product of the lithosphere which is critical in meeting our fuel needs. While most of South Africa's oil is imported and then processed at a refinery in either Durban, Cape Town or Sasolburg, some is extracted from coal. The technology behind this type of extraction has largely been developed by SASOL (South African Coal, Oil and Gas Corporation). Oil, like coal, is organic in origin and normally forms from organic deposits on the ocean floor. Oil requires unique geological and geochemical conditions in order to be produced. Part of this process involves the burial of organic-rich sediments under extremely high temperatures and pressures. The oil that is produced is then pushed out into nearby sedimentary layers. Oil will then move upwards until it is trapped by an impermeable rock layer. It accumulates here, and can then be accessed by oil rigs and other advanced equipment.

21.5 Mining and Mineral Processing: Gold

21.5.1 Introduction

Gold was discovered in South Africa in the late 1800's and since then has played a very important role in South Africa's *history* and *economy*. Its discovery brought many foreigners into South Africa, who were lured by the promises of wealth. They set up small mining villages, which later grew into larger settlements, towns and cities. One of the first of these settlements was the beginning of present-day Johannesburg, also known as 'Egoli' or 'Place of Gold'.

Most of South Africa's gold is concentrated in the 'Golden Arc', which stretches from Johannesburg to Welkom. Geologists believe that, millions of years ago, this area was a massive inland lake. Rivers feeding into this lake brought sand, silt, pebbles and fine particles of gold and deposited them over a long period of time. Eventually these deposits accumulated and became compacted to form gold-bearing sedimentary rock or **gold reefs**. It is because of this complex, but unique, set of circumstances that South Africa's gold deposits are so concentrated in that area. In other countries like Zimbabwe, gold occurs in smaller 'pockets', which are scattered over a much greater area.

21.5.2 Mining the Gold

A number of different techniques can be used to mine gold. The three most common methods in South Africa are **panning**, **open cast** and **shaft** mining.

1. **Panning**

   Panning for gold is a manual technique that is used to sort gold from other sediments. Wide, shallow pans are filled with sand and gravel (often from river beds) that may contain gold. Water is added and the pans are shaken so that the gold is sorted from the rock and other materials. Because gold is much more dense, it settles to the bottom of the pan. **Pilgrim's Rest** in Mpumalanga, was the first site for gold panning in South Africa.

2. **Open cast mining**

   This is a form of surface mining. Surface layers of rock and sediments are removed so that the deeper gold rich layers can be reached. This type of mining is not suitable if the gold is buried very deep below the surface.

3. **Shaft mining**

   South Africa's thin but extensive gold reefs slope at an angle underneath the ground, and this means that some deposits are very deep and often difficult to reach. Shaft mining is needed to reach the gold ore. After the initial drilling, blasting and equipping of a mine shaft, tunnels are built leading outwards from the main shaft so that the gold reef can be reached. Shaft mining is a dangerous operation, and roof supports are needed so that the rock does not collapse. There are also problems of the intense heat and high pressure below the surface which make shaft mining very complex, dangerous and expensive. A diagram illustrating open cast and shaft mining is shown in figure 21.2.

21.5.3 Processing the gold ore

For every ton of ore that is mined, only a very small amount of gold is extracted. A number of different methods can be used to separate gold from its ore, but one of the more common

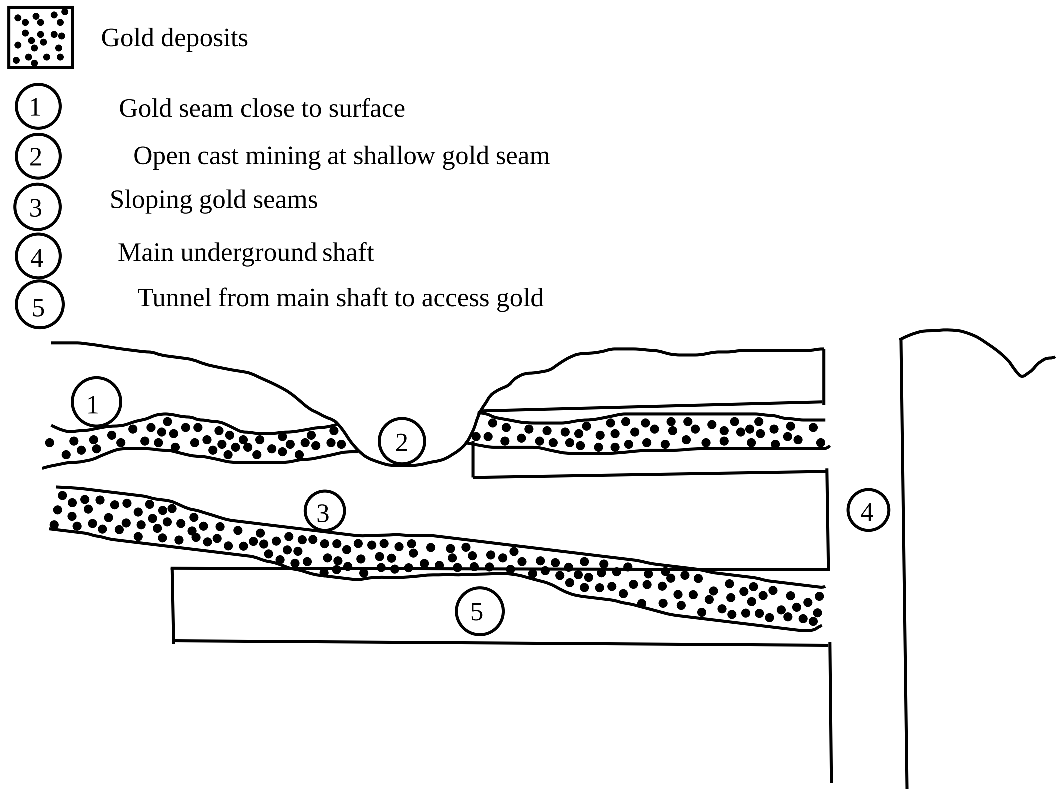


Figure 21.2: Diagram showing open cast and shaft mining

methods is called **gold cyanidation**.

In the process of gold cyanidation, the ore is crushed and then cyanide solution is added so that the gold particles are chemically dissolved from the ore. In this step of the process, gold is oxidised. Zinc dust is then added to the cyanide solution. The zinc takes the place of the gold, so that the gold is precipitated out of the solution. This process is shown in figure 21.3.

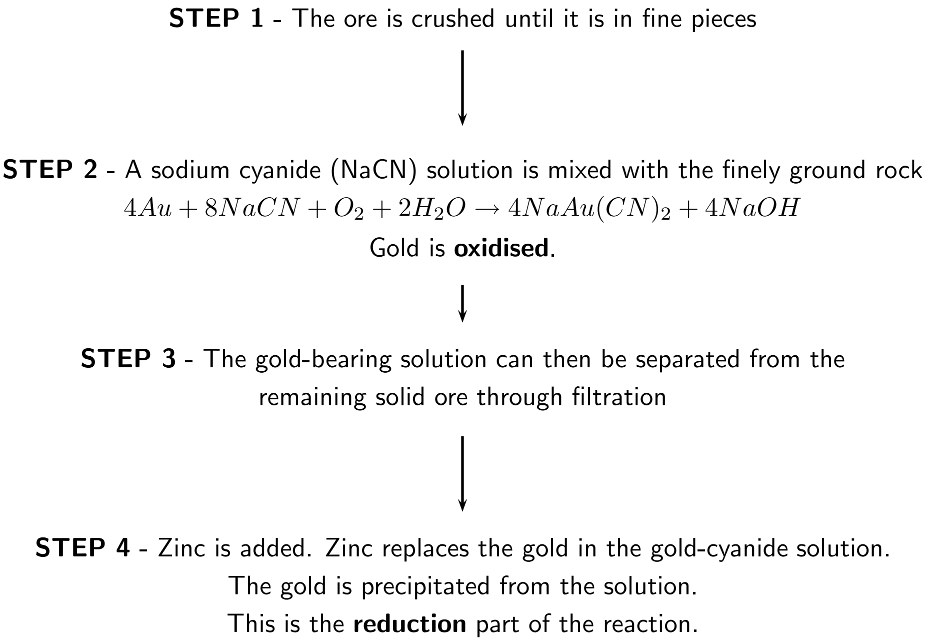
Another method that is used to process gold is called the 'carbon-in-pulp' (CIP) method. This method makes use of the high affinity that activated carbon has for gold, and there are three stages to the process. The first stage involves the *absorption* of gold in the cyanide solution to carbon. In the *elution* stage, gold is removed from the carbon into an alkaline cyanide solution. In the final stage, *electro-winning* is used to remove gold from the solution through a process of electrolysis. Gold that has been removed is deposited on steel wool electrodes. Both the carbon and the acid are then treated so that they can be re-used.

21.5.4 Characteristics and uses of gold

Gold has a number of uses because of its varied and unique characteristics. Below is a list of some of these characteristics that have made gold such a valuable metal:

- *Shiny*

  Gold's beautiful appearance has made it one of the favourite metals for use in jewelery.



STEP 1 - The ore is crushed until it is in fine pieces

STEP 2 - A sodium cyanide (NaCN) solution is mixed with the finely ground rock

$$4Au + 8NaCN + O_2 + 2H_2O \rightarrow 4NaAu(CN)_2 + 4NaOH$$

Gold is **oxidised**.

STEP 3 - The gold-bearing solution can then be separated from the remaining solid ore through filtration

STEP 4 - Zinc is added. Zinc replaces the gold in the gold-cyanide solution. The gold is precipitated from the solution. This is the **reduction** part of the reaction.

Figure 21.3: Flow diagram showing how gold is processed

- *Durable*

  Gold does not tarnish or corrode easily, and therefore does not deteriorate in quality. It is sometimes used in dentistry to make the crowns for teeth.

- *Malleable and ductile*

  Since gold can be bent and twisted into shape, as well as being flattened into very thin sheets, it is very useful in fine wires and to produce sheets of gold.

- *Good conductor*

  Gold is a good conductor of electricity and is therefore used in transistors, computer circuits and telephone exchanges.

- *Heat ray reflector*

  Because gold reflects heat very effectively, it is used in space suits and in vehicles. It is also used in the protective outer coating of artificial satellites. One of the more unusual applications of gold is its use in firefighting, where a thin layer of gold is placed in the masks of the firefighters to protect them from the heat.

Activity :: Case Study : Dropping like a gold balloon

Read the article below, which has been adapted from one that appeared in the *Financial Mail* on 15th April 2005 and then answer the questions that follow.

> As recently as 1980, South Africa accounted for over 70% of world gold production. In 2004, that figure was a dismal 14%. Chamber of Mines figures showed that SA's annual gold production last year slipped to its lowest level since 1931.
>
> Chamber economist Roger Baxter says the 'precipitous' fall in production was caused by the dual impact of the fall in the rand gold price due to the strong rand, and the continued upward rise in costs. Many of these costs, laments Baxter, are 'costs we do not have control over'. These include

water, transport, steel and labour costs, which rose by 13% on average in 2004.

He provides a breakdown of the cost components faced by mines:

- Water prices have risen by 10% per year for the past 3 years
- Steel prices have increased by double-digit rates for each of the past 3 years
- Spoornet's tariffs rose 35% in 2003 and 16.5% in 2004
- Labour costs, which make up 50% of production costs, rose above inflation in 2003 and 2004

At these costs, and at current rand gold prices, about 10 mines, employing 90 000 people, are marginal or loss-making, says Baxter.

1. Refer to the table below showing SA's gold production in tons between 1980 and 2004.

Year	**Production (t)**
1980	675
1985	660
1990	600
1995	525
2000	425
2004	340

Draw a line graph to illustrate these statistics.

2. What percentage did South Africa's gold production contribute towards global production in:
   (a) 1980
   (b) 2004
3. Outline two reasons for this drop in gold production.
4. Briefly explain how the increased cost of resources such as water contributes towards declining profitability in gold mines.
5. Suggest a reason why the cost of *steel* might affect gold production.
6. Suggest what impact a decrease in gold production is likely to have on...
   (a) South Africa's economy
   (b) mine employees
7. Find out what the current price of gold is. Discuss why you think gold is so expensive.

21.5.5 Environmental impacts of gold mining

However, despite the incredible value of gold and its usefulness in a variety of applications, all mining has an environmental cost. The following are just a few of the environmental impacts of gold mining:

- *Resource consumption*

  Gold mining needs large amounts of electricity and water.

- *Poisoned water*

  Acid from gold processing can leach into nearby water systems such as rivers, causing damage to animals and plants, as well as humans that may rely on that water for drinking. The disposal of other toxic waste (e.g. cyanide) can also have a devastating effect on biodiversity.

- *Solid waste*

  This applies particularly to open pit mines, where large amounts of soil and rock must be displaced in order to access the gold reserves. Processing the gold ore also leaves solid waste behind.

- *Air pollution*

  Dust from open pit mines, as well as harmful gases such as sulfur dioxide and nitrogen dioxide which are released from the furnaces, contribute to air pollution.

- *Threaten natural areas*

  Mining activities often encroach on protected areas and threaten biodiversity in their operation areas.

Activity :: Discussion : Mine rehabilitation

There is a growing emphasis on the need to rehabilitate old mine sites that are no longer in use. If it is too difficult to restore the site to what it was before, then a new type of land use might be decided for that area. Any mine rehabilitation programme should aim to achieve the following:

- ensure that the site is safe and stable
- remove pollutants that are contaminating the site
- restore the biodiversity that was there before mining started
- restore waterways to what they were before mining

There are different ways to achieve these goals. Plants for example, can be used to remove metals from polluted soils and water, and can also help to stabilise the soil so that other vegetation can grow. Land contouring can help to restore drainage in the area.

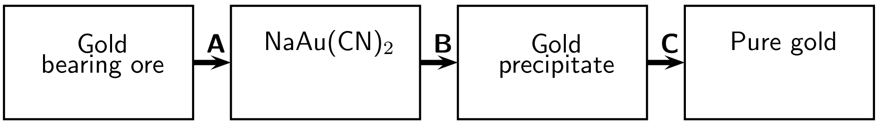
Discussion:

In groups of 3-4, discuss the following questions:

1. What are the main benefits of mine rehabilitation?
2. What are some of the difficulties that may be experienced in trying to rehabilitate a mine site?
3. Suggest some creative ideas that could be used to encourage mining companies to rehabilitate old sites.
4. One rehabilitation project that has received a lot of publicity is the rehabilitation of dunes that were mined for titanium by Richards Bay Minerals (RBM). As a group, carry out your own research to try to find out more about this project.
    - What actions did RBM take to rehabilitate the dunes?
    - Was the project successful?
    - What were some of the challenges faced?

Exercise: Gold mining

Mapungubwe in the Limpopo Province is evidence of gold mining in South Africa as early as 1200. Today, South Africa is a world leader in the technology of gold mining. The following flow diagram illustrates some of the most important steps in the recovery of gold from its ore.



1. Name the process indicated by A.
2. During process A, gold is extracted from the ore. Is gold oxidised or reduced during this process?
3. Use oxidation numbers to explain your answer to the question above.
4. Name the chemical substance that is used in process B.
5. During smelting (illustrated by C in the diagram), gold is sent into a calcining furnace. Briefly explain the importance of this process taking place in the furnace.
6. The recovery of gold can have a negative impact on water in our country, if not managed properly. State at least one negative influence that the recovery of gold can have on water resources and how it will impact on humans and the environment.

21.6 Mining and mineral processing: Iron

Iron is one of the most abundant metals on Earth. Its concentration is highest in the core, and lower in the crust. It is extracted from **iron ore** and is almost never found in its elemental form. Iron ores are usually rich in **iron oxide** minerals and may vary in colour from dark grey to rusty red. Iron is usually found in minerals such as magnetite (Fe_3O_4) and hematite (Fe_2O_3). Iron ore also contains other elements, which have to be removed in various ways. These include silica (Si), phosphorus (P), aluminium (Al) and sulfur (S).

21.6.1 Iron mining and iron ore processing

One of the more common methods of mining for iron ore is **open cast mining**. Open cast mining is used when the iron ore is found near the surface. Once the ore has been removed, it needs to be crushed into fine particles before it can be processed further.

As mentioned earlier, iron is commonly found in the form of **iron oxides**. To create pure iron, the ore must be **smelted** to remove the oxygen.

Definition: Smelting
Smelting is a method used to extract a metal from its ore and then purify it.

Smelting usually involves heating the ore and also adding a reducing agent (e.g. carbon) so that the metal can be freed from its ore. The bonds between iron and oxygen are very strong, and therefore it is important to use an element that will form stronger bonds with oxygen that the iron. This is why carbon is used. In fact, carbon monoxide is the main ingredient that is needed to strip oxygen from iron. These reactions take place in a **blast furnace**.

A blast furnace is a huge steel container many metres high and lined with heat-resistant material. In the furnace the solid raw materials, i.e. iron ore, carbon (in the form of 'coke', a type of coal) and a flux (e.g. limestone) are fed into the top of the furnace and a blast of heated air is forced into the furnace from the bottom. Temperatures in a blast furnace can reach 2000°C. A simple diagram of a blast furnace is shown in figure 21.4. The equations for the reactions that take place are shown in the flow diagram below.

STEP 1: Production of carbon monoxide

$$C + O_2 \rightarrow CO_2$$

$$CO_2 + C \rightarrow 2CO$$

STEP 2: Reduction of iron oxides takes place in a number of stages to produce iron.

$$3Fe_2O_3 + CO \rightarrow 2Fe_3O_4 + CO_2$$

$$Fe_3O_4 + CO \rightarrow 3FeO + CO_2$$

$$FeO + CO \rightarrow Fe + CO_2$$

STEP 3: Fluxing

The flux is used to melt impurities in the ore. A common flux is limestone ($CaCO_3$). Common impurities are silica, phosphorus (makes steel brittle), aluminium and sulfur (produces SO_2 gases during smelting and interferes with the smellting process).

$$CaCO_3 \rightarrow CaO + CO_2$$

$$CaO + SiO_2 \rightarrow CaSiO_3$$

In step 3, the calcium carbonate breaks down into calcium oxide and carbon dioxide. The calcium oxide then reacts with silicon dioxide (the impurity) to form a **slag**. In this case the slag is the $CaSiO_3$. The slag melts in the furnace, whereas the silicon dioxide would not have, and floats on the more dense iron. This can then be separated and removed.

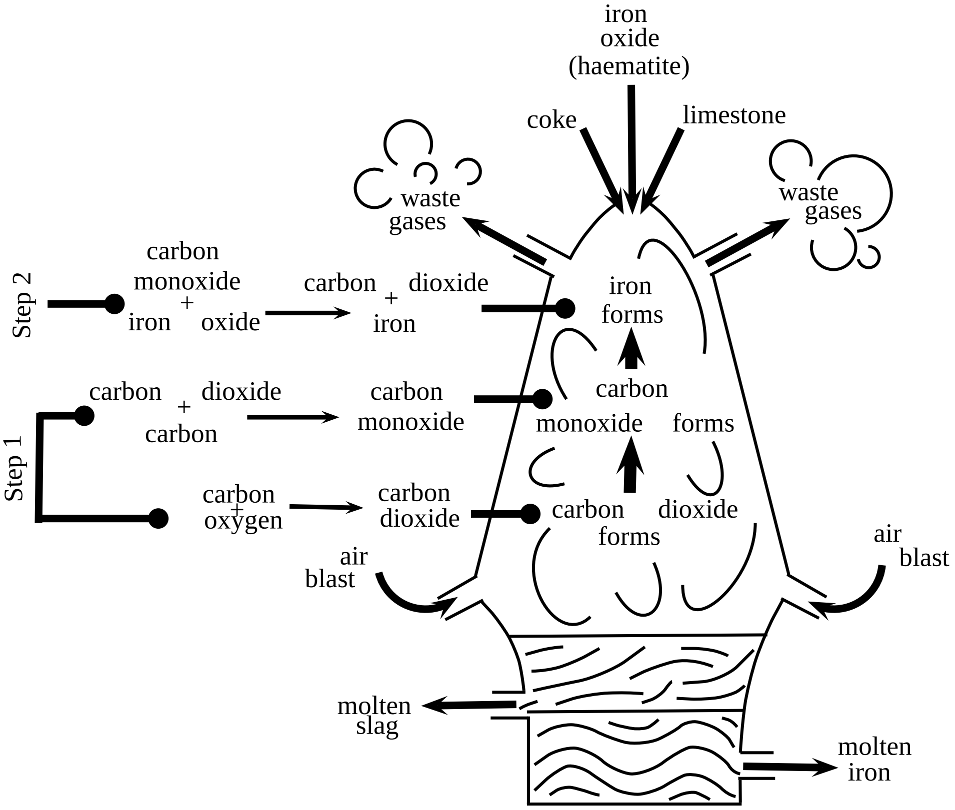


Figure 21.4: A blast furnace, showing the reactions that take place to produce iron

21.6.2 Types of iron

Iron is the most used of all the metals. Its combination of low cost and high strength make it very important in applications such as industry, automobiles, the hulls of large ships and in the structural components of buildings. Some of the different forms that iron can take include:

- **Pig iron** is raw iron and is the direct product when iron ore and coke are smelted. It has between 4% and 5% carbon and contains varying amounts of contaminants such as sulfur, silicon and phosphorus. Pig iron is an intermediate step between iron ore, cast iron and steel.
- **Wrought iron** is commercially pure iron and contains less than 0.2% carbon. It is tough, malleable and ductile. Wrought iron does not rust quickly when it is used outdoors. It has mostly been replaced by mild steel for 'wrought iron' gates and blacksmithing. Mild steel does not have the same corrosion resistance as true wrought iron, but is cheaper and more widely available.
- **Steel** is an alloy made mostly of iron, but also containing a small amount of carbon. Elements other than carbon can also be used to make alloy steels. These include manganese and tungsten. By varying the amounts of the alloy elements in the steel, the following characteristics can be altered: hardness, elasticity, ductility and tensile strength.
- **Corrugated iron** is actually sheets of galvanised steel that have been rolled to give them a corrugated pattern. Corrugated iron is a common building material.

One problem with iron and steel is that pure iron and most of its alloys rust. These products therefore need to be protected from water and oxygen, and this is done through painting, galvanisation and plastic coating.

Iron is also a very important element in all living organisms. One important role that iron plays is that it is a component of the protein **haemoglobin** which is the protein in blood. It is the iron in the haemoglobin that helps to attract and hold oxygen so that this important gas can be transported around the body in the blood, to where it is needed.

21.6.3 Iron in South Africa

The primary steel industry is an important part of the South African economy and it generates a great deal of foreign exchange.

- About 40 million tons of iron ore is mined annually in South Africa. Approximately 15 million tons are consumed locally, and the remaining 25 million tons are exported.
- South Africa is ranked about 20th in the world in terms of its crude steel production.
- South Africa is the largest steel producer in Africa.
- South Africa exports crude steel and finished steel products, and a lot is also used locally.
- Some of the products that are manufactured in South Africa include reinforcing bars, railway track material, wire rod, plates and steel coils and sheets.

Exercise: Iron

Iron is usually extracted from heamatite (iron(III)oxide). Iron ore is mixed with limestone and coke in a blast furnace to produce the metal. The following incomplete word equations describe the extraction process:

A coke + oxygen → gasX

B gasX + coke → gasY

C iron(III)oxide + gasY → iron + gasX

1. Name the gases X and Y.
2. Write a balanced chemical equation for reaction C.
3. What is the function of gas Y in reaction C?
4. Why is limestone added to the reaction mixture?
5. Briefly describe the impact that the mining of iron has on the economy and the environment in our country.

(DoE Exemplar Paper, Grade 11, 2007)

21.7 Mining and mineral processing: Phosphates

A phosphate is a salt of **phosphoric acid** (H_3PO_4). Phosphates are the naturally occurring form of the element phosphorus. Phosphorus is seldom found in its pure elemental form, and **phosphate** therefore refers to a rock or ore that contains phosphate ions. The chemical formula for the phosphate ion is PO_4^{3-}.

21.7.1 Mining phosphates

Phosphate is found in beds in sedimentary rock, and has to be quarried to access the ore. A quarry is a type of open pit mine that is used to extract ore. In South Africa, the main phosphate producer is at the Palaborwa alkaline igneous complex, which produces about 3 million tons of ore per year. The ore is crushed into a powder and is then treated with sulfuric acid to form a superphosphate ($Ca(H_2PO_4)_2$), which is then used as a fertilizer. In the equation below, the phosphate mineral is calcium phosphate ($Ca_3(PO_4)_2$.

$$Ca_3(PO_4)_2 + 2H_2SO_4 \rightarrow Ca(H_2PO_4)_2 + 2CaSO_4$$

Alternatively, the ore can be treated with concentrated phosphoric acid, in which case the reaction looks like this:

$$3Ca_3(PO_4)_2.CaF_2 + 4H_3PO_4 + 9H_2O \rightarrow 9Ca(H_2PO_4)_2 + CaF_2$$

21.7.2 Uses of phosphates

Phosphates are mostly used in **agriculture**. Phosphates are one of the three main nutrients needed by plants, and they are therefore an important component of **fertilisers** to stimulate plant growth.

Exploring the lithosphere for minerals is not a random process! **Geologists** help to piece together a picture of what past environments might have been like, so that predictions can be made about where minerals might have a high concentration. **Geophysicists** measure gravity, magnetics and the electrical properties of rocks to try to make similar predictions, while **geochemists** sample the soils at the earth's surface to get an idea of what lies beneath them. You can see now what an important role scientists play in mineral exploration!

Exercise: Phosphates

Rock phosphate [$Ca_{10}(PO_4)_6F_2$], mined from open pit mines at Phalaborwa, is an important raw material in the production of fertilisers. The following two reactions are used to transform rock phosphate into water soluble phosphates:

A: $Ca_{10}(PO_4)_6F_2 + 7X + 3H_2O \rightarrow 3Ca(H_2PO_4)_2H_2O + 2HF + 7CaSO_4$

B: $Ca_{10}(PO_4)_6F_2 + 14Y + 10H_2O \rightarrow 10Ca(H_2PO_4)_2H_2O + 2HF$

1. Identify the acids represented by X and Y.
2. Despite similar molecular formulae, the products $Ca(H_2PO_4)_2$ formed in the two reactions have different common names. Write down the names for each of these products in reactions A and B.
3. Refer to the products in reactions A and B and write down TWO advantages of reaction B over reaction A.
4. Why is rock phosphate unsuitable as fertiliser?
5. State ONE advantage and ONE disadvantage of phosphate mining.

(DoE Exemplar Paper, Grade 11, 2007)

Activity :: Case Study : Controversy on the Wild Coast - Titanium mining

Read the extract below, which has been adapted from an article that appeared in the Mail and Guardian *on 4th May 2007, and then answer the questions that follow.*

> A potentially violent backlash looms in Pondoland over efforts by an Australian company to persuade villagers to back controversial plans to mine an environmentally sensitive strip of the Wild Coast. The mining will take place in the Xolobeni dunes, south of Port Edward. The application has outraged environmental groups, largely because the proposed mining areas form part of the Pondoland centre of endemism, which has more species than the United Kingdom, some of which are endemic and facing extinction.
>
> Exploratory drilling revealed Xolobeni has the world's 10th largest titanium deposit, worth about R11 billion. The amount of money that will be spent over the mine's 22 years, including a smelter, is estimated at R1.4 billion. The Australian mining company predicts that 570 direct jobs will be created.
>
> But at least two communities fiercely oppose the mining plans. Some opponents are former miners who fear Gauteng's mine dumps and compounds will be replicated on the Wild Coast. Others are employees of failed ecotourism ventures, who blame the mining company for their situation. Many are suspicious of outsiders. The villagers have also complained that some of the structures within the mining company are controlled by business leaders with political connections, who are in it for their own gain. Intimidation of people who oppose the mining has also been alleged. Headman Mandoda Ndovela was shot dead after his outspoken criticism of the mining.
>
> Mzamo Dlamini, a youth living in one of the villages that will be affected by the mining, said 10% of the Amadiba 'who were promised riches by the mining company' support mining. 'The rest say if people bring those machines, we will fight.'

1. Explain what the following words means:
    (a) endemic
    (b) smelter
    (c) ecotourism
2. What kinds of 'riches' do you think the Amadiba people have been promised by the mining company?
3. In two columns, list the potential **advantages** and **disadvantages** of mining in this area.
4. Imagine that you were one of the villagers in this area. Write down *three questions* that you would want the mining company to answer before you made a decision about whether to oppose the mining or not. Share your ideas with the rest of the class.
5. Imagine that you are an environmentalist. What would your main concerns be about the proposed mining project? Again share your answers with the rest of the class.

21.8 Energy resources and their uses: Coal

The products of the lithosphere are also important in meeting our **energy needs**. Coal is one product that is used to produce energy. In South Africa, coal is particularly important because most of our electricity is generated using coal as a fuel. South Africa is the world's sixth largest coal producer, with Mpumalanga contributing about 83% of our total production. Other areas in which coal is produced, include the Free State, Limpopo and KwaZulu-Natal. One of the problems with coal however, is that it is a **non-renewable resource**, meaning that once all resources have been used up, it cannot simply be produced again. Burning coal also produces large quantities of greenhouse gases, which may play a role in global warming. At present, ESKOM, the South African government's electric power producer, is the coal industry's main customer.

21.8.1 The formation of coal

Coal is what is known as a **fossil fuel**. A fossil fuel is a *hydrocarbon* that has been formed from organic material such as the remains of plants and animals. When plants and animals decompose, they leave behind organic remains that accumulate and become compacted over millions of years under sedimentary rock. Over time, the *heat* and *pressure* in these parts of the earth's crust also increases, and coal is formed. When coal is burned, a large amount of heat energy is released, which is used to produce electricity. **Oil** is also a fossil fuel and is formed in a similar way.

Definition: Fossil Fuel
A fossil fuel is a hydrocarbon that is formed from the fossilised remains of dead plants and animals that have been under conditions of intense heat and pressure for millions of years.

21.8.2 How coal is removed from the ground

Coal can be removed from the crust in a number of different ways. The most common methods used are *strip mining*, *open cast mining* and *underground mining*.

1. **Strip mining**

   Strip mining is a form of surface mining that is used when the coal reserves are very shallow. The *overburden* (overlying sediment) is removed so that the coal seams can be reached. These sediments are replaced once the mining is finished, and in many cases, attempts are made to *rehabilitate* the area.

2. **Open cast mining**

   Open cast mining is also a form of surface mining, but here the coal deposits are too deep to be reached using strip mining. One of the environmental impacts of open cast mining is that the overburden is dumped somewhere else away from the mine, and this leaves a huge pit in the ground.

3. **Underground mining**

   Undergound mining is normally used when the coal seams are amuch deeper, usually at a depth greater than 40 m. As with shaft mining for gold, the problem with underground mining is that it is very dangerous, and there is a very real chance that the ground could collapse during the mining if it is not supported. One way to limit the danger is to use *pillar support* methods, where some of the ground is left unmined so that it forms pillars to support the roof. All the other surfaces underground will be mined. Using another method called *longwalling*, the roof is allowed to collapse as the mined-out area moves along. In South Africa, only a small percentage of coal is mined in this way.

21.8.3 The uses of coal

Although in South Africa, the main use of coal is to produce electricity, it can also be used for other purposes.

1. **Electricity**

   In order to generate electricity, solid coal must be crushed and then burned in a furnace with a boiler. A lot of steam is produced and this is used to spin turbines which then generate electricity.

2. **Gasification**

   If coal is broken down and subjected to very high temperatures and pressures, it forms a *synthesis gas*, which is a mix of carbon dioxide and hydrogen gases. This is very important in the *chemical industry* (refer to chapter 23).

3. **Liquid fuels**

   Coal can also be changed into liquid fuels like petrol and diesel using the **Fischer-Tropsch process**. In fact, South Africa is one of the leaders in this technology (refer to chapter 23). The only problem is that producing liquid fuels from coal, rather than refining petroleum that has been drilled, releases much greater amounts of carbon dioxide into the atmosphere, and this contributes further towards global warming.

21.8.4 Coal and the South African economy

In South Africa, the coal industry is second only to the gold industry. More than this, South Africa is one of the world's top coal *exporters*, and also one of the top *producers*. Of the coal that is produced, most is used locally to produce electricity and the rest is used in industry and domestically.

The problem with coal however, is that it is a **non-renewable resource** which means that once all the coal deposits have been mined, there will be none left. Coal takes such a long time to form, and requires such specific environmental conditions, that it would be impossible for coal to re-form at a rate that would keep up with humankind's current consumption. It is therefore very important that South Africa, and other countries that rely on coal, start to look for alternative energy resources.

21.8.5 The environmental impacts of coal mining

There are a number of environmental impacts associated with coal mining.

- *Visual impact and landscape scars*

  Coal mining leaves some very visible scars on the landscape, and destroys biodiversity (e.g. plants, animals). During strip mining and open cast mining, the visual impact is particularly bad, although this is partly reduced by rehabilitation in some cases.

- *Spontaneous combustion and atmospheric pollution*

  Coal that is left in mine dumps may spontaneously combust, producing large amounts of sulfurous smoke which contributes towards atmospheric pollution.

- *Acid formation*

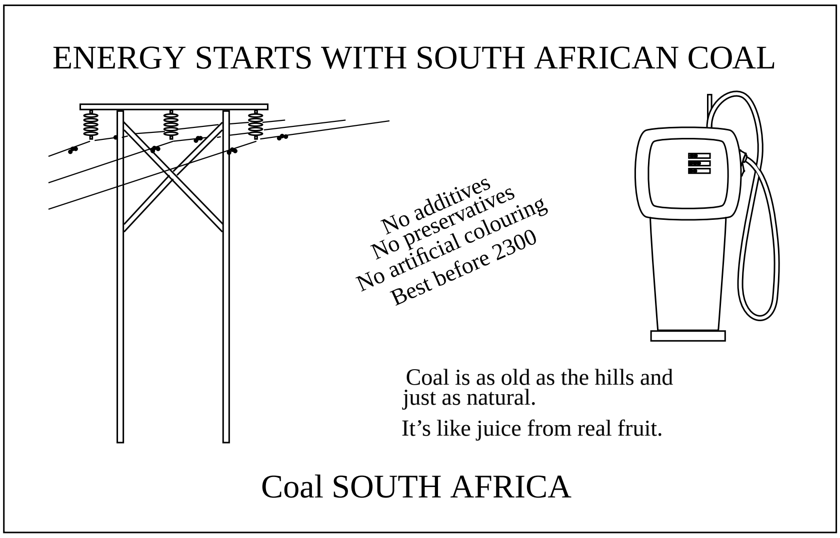
  Waste products from coal mining have a high concentration of sulfur compounds. When these compounds are exposed to water and oxygen, sulfuric acid is formed. If this acid washes into nearby water systems, it can cause a lot of damage to the ecosystem. Acid can also leach into soils and alter its acidity. This in turn affects what will be able to grow there.

- *Global warming*

  As was discussed earlier, burning coal to generate electricity produces *carbon dioxide* and *nitrogen oxides* which contribute towards global warming (refer to chapter 22). Another gas that causes problems is *methane*. All coal contains methane, and deeper coal contains the most methane. As a greenhouse gas, methane is about twenty times more potent than carbon dioxide.

It is easy to see how mining, and many other activities including industry and vehicle transport, contribute towards Global Warming. It was for this reason that South Africa joined the **Carbon Sequestration Leadership Forum (CSLF)**. The forum is an international climate change initiative that focuses on developing cost effective technologies to separate and capture carbon dioxide from the atmosphere so that it can be stored in some way. The CSLF also aims to make these technologies as widely available as possible.

Exercise: Coal in South Africa
The following advertisement appeared in a local paper:



ENERGY STARTS WITH SOUTH AFRICAN COAL

No additives
No preservatives
No artificial colouring
Best before 2300

Coal is as old as the hills and just as natural.

It's like juice from real fruit.

Coal SOUTH AFRICA

1. *"Coal is as old as the hills, and just as natural."* Is this statement TRUE? Motivate your answer by referring to how coal is formed.
2. Coal is a non-renewable energy source. Quote a statement from the advertisement that gives an indication that coal is non-renewable. Give a reason for your choice.
3. Is coal actually a healthy source of energy? Motivate your answer by referring to all influences that coal and coal mining have on both humans and the environment.
4. Why is coal used as a primary energy source in South Africa?

(DoE Exemplar Paper 2, Grade 11, 2007)

21.9 Energy resources and their uses: Oil

Oil is another product of the lithosphere which is very important in meeting our fuel needs.

21.9.1 How oil is formed

Oil is formed in a very similar way to coal, except that the organic material is laid down in **oceans**. Organisms such as zooplankton and algae settle to the ocean floor and become buried under layers of mud. Over time, as these layers of sediment accumulate and the heat and pressure also increase, the organic material changes to a waxy material called *kerogen*. Eventually, with continuing heat and pressure, liquid and gas **hydrocarbons** are formed. These hydrocarbons are lighter than rock and therefore move upwards through the rock layers before being trapped by an impermeable layer. Here the oil will slowly accumulate until there is enough that it can be accessed by oil rigs and other equipment. **Crude oil** or **petroleum**, is actually a mixture of hydrocarbons (mostly alkanes) of different lengths, ranging from 5 carbons to 18 carbons in the hydrocarbon chain. If the mixture contains mostly short hydrocarbons, then it is a gas called **natural gas**. As the hydrocarbon chains in the mixture become longer, the product becomes more and more solid. Coal is made up of the longest hydrocarbons. For more information on hydrocarbons, refer to chapter 9.

21.9.2 Extracting oil

When enough oil has accumulated in a well, it becomes economically viable to try to extract it either through **drilling** or **pumping**. If the pressure in the oil reservoir is high, the oil is forced naturally to the surface. This is known as *primary recovery* of oil. If the pressure is low, then pumps must be used to extract it. This is known as *secondary recovery*. When the oil is very difficult to extract, steam injection into the reservoir can be used to heat the oil, reduce its viscosity and make it easier to extract.

While most of South Africa's oil is imported and then processed at a refinery in either Durban, Cape Town or Sasolburg, some is extracted from coal, as discussed in section 21.8.

21.9.3 Other oil products

Oil can also be used to make a variety of different products. You will find more information on this in chapter 23.

- *Fractional distillation*

  Fractional distillation is the separation of a mixture into the parts that make it up. In oil refineries, crude oil is separated into useful products such as asphalt, diesel, fuel oil, gasoline, kerosine, liquid petroleum gas (LPG) and tar, to name just a few.

- *Cracking*

  There are two types of cracking, *steam cracking* and *hydrocracking*. Cracking is used to change heavy hydrocarbons such as petroleum into lighter hydrocarbons such as fuels (LPG and gasoline), plastics (ethylene) and other products that are needed to make fuel gas (propylene).

21.9.4 The environmental impacts of oil extraction and use

Some of the key environmental impacts associated with the extraction and use of oil are as follows:

- *Pollution*

  Exploring the oceans for oil, and the actual drilling process, can result in major pollution.

- *Ecosystem impacts*

  Dredging the ocean floors for oil can disrupt seabed ecosystems.

- *Global warming*

  Burning oil as a fuel source produces carbon dioxide, which contributes towards global warming.

21.10 Alternative energy resources

As the world's population increases, so does the demand for energy. As we have already mentioned, many of our energy resources are **non-renewable** and will soon run out. In addition, many of the fuels that we use produce large amounts of greenhouse gases, which can contribute towards global warming. If we are to maintain the quality and health of our planet, and also meet our growing need for energy, we will need to investigate alternative energy resources. In this next section, we are going to take a closer look at some of these possible alternatives. Many of these options are very controversial, and may have both pros and cons.

- *Nuclear power*

  Another element that is found in the crust, and which helps to meet our energy needs, is **uranium**. Uranium produces energy through the process of *nuclear fission* (chapter **??**). Neutrons are aimed at the nucleii of the uranium atoms in order to split them. When the nucleus of a uranium atom is split, a large amount of energy is released as heat. This heat is used to produce steam, which turns turbines to generate electricity. Uranium is produced as a by-product of gold in some mines in the Witwatersrand, and as a by-product in some copper mines, for example in Palaborwa. Many people regard this type of nuclear power as relatively environmentally friendly because it doesn't produce a lot of greenhouse gases. However, generating nuclear power does produce radioactive wastes, which must be carefully disposed of in order to prevent contamination. There are also concerns around leaking of nuclear materials.

- *Natural gas*

  Natural gas is formed in a similar way to oil and is often located above oil deposits in the earth's crust. 'Natural gas' refers to a hydrocarbon gas, composed mostly of methane. It is highly combustible and produces low emissions.

  In June 2002, construction began on a pipeline that would stretch for 865 km between Mozambique and South Africa. Mozambique has large sources of under-utilised natural gas and so an agreement was reached between SASOL and the South African and Mozambican governments to build the pipeline, which would transport natural gas from Mozambique to South Africa. The benefits of natural gas include the fact that it is a clean-burning fossil fuel and few by-products are emitted as pollutants. It is also an economical and efficient energy source as the gas can easily be piped directly to a customer's facility.

- *Biofuels*

  In many parts of the world, ethanol is currently being used as a substitute for crude petroleum. Ethanol can be produced through the fermentation of sugar-containing products such as sugar cane. One of the problems with this however, is the vast areas of land that are needed to cultivate the necessary crops. Crops such as maize can also be used in the process. In South Africa, a company called 'Ethanol Africa' has been set up by commercial farmers to convert their surplus maize into environmentally-friendly biofuel, and plans are underway to establish ethanol plants in some of the maize-producing provinces.

- *Hydropower*

  Hydropower produces energy from the action of falling water. As water falls from a height, the energy is used to turn turbines which produce electricity. However, for hydropower to be effective, a large dam is needed to store water. The building of a dam comes with its own set of problems such as the expense of construction, as well as the social and environmental impacts of relocating people (if the area is populated),and disrupting a natural river course.

- *Solar energy*

  Solar energy is energy from the sun. The sun's radiation is trapped in solar panels and is then converted into electricity. While this process is environmentally friendly, and solar energy is a renewable resource, the supply of radiation is not constant (think for example of cloudy days, and nights), and the production of electricity is not efficient. Solar energy can however meet small energy needs such as the direct heating of homes.

- *Geothermal energy*

  This type of energy comes from the natural heat below the Earth's surface. If hot underground steam can be tapped and brought to the surface, it has the potential to produce electricity.

Activity :: Discussion : Using energy wisely

The massive power cuts or 'load shedding' that South Africans began to experience at the beginning of 2008, were a dramatic wake-up call to the growing energy crisis that the country faces.

There are alternative energy sources available, but they will take years to become functional, and many of them have their own problems. Another way to look at the problem, is to put the focus on reducing how much energy is *used* rather than focusing only on ways to meet the growing demand.

1. In your groups, discuss ways that each of the following groups of people could save energy.
   (a) industries
   (b) domestic users
   (c) farmers
2. Discuss creative incentives that could be used to encourage each of these groups to reduce their energy consumption.

21.11 Summary

- The **lithosphere** is the solid, outermost part of our planet and contains many important metal elements such as gold and iron, as well as products that are needed to produce energy.
- These elements are seldom found in their pure form, but rather as **minerals** in **rocks**.
- A **mineral** is formed through geological processes. It can either be a pure element (e.g. gold) or may consist of a number of different elements e.g. the gold-bearing mineral calaverite ($AuTe_2$).
- A **rock** is an aggregate of a number of different minerals.
- An **ore** is rock that contains minerals which make it valuable for mining.
- Minerals have been used throughout **history**. As new metals and minerals were discovered, important growth took place in industry, agriculture and technology.
- **Gold** is one of the most important metals in the history of South Africa. It was the discovery of gold that led to an influx of fortune-seeking foreigners, and a growth in mining villages and towns.
- Most of South Africa's gold is concentrated in the 'Golden Arc' in the area between Johannesburg and Welkom.
- Three methods are used to obtain gold from the lithosphere: **panning**, **open cast mining** and **shaft mining**.
- Gold ore must be processed so that the metal can be removed. One way to process the ore after it has been crushed is a method called **gold cyanidation**. A cyanide solution is added to the crushed ore so that a gold-cyanide solution is formed. Zinc is then added to this solution so that the gold is precipitated out.
- Gold has a number of important **characteristics** which make it a useful metal for jewelery and other applications. The metal is shiny, durable, malleable, ductile, is a good conductor of electricity and is also a good heat reflector.
- Gold mining has a number of **environmental impacts**, which include resource consumption, air pollution, poisoned water, solid waste and the destruction of biodiversity in natural areas.
- **Mine rehabilitation** is one way of restoring old mine sites to what they were like before.
- **Iron** is another important metal and is used in industry, furniture and building materials.
- Iron is usually found in minerals such as **iron oxides**. These minerals must be processed to remove the metal.
- When iron ore is **processed**, a blast furnace is used. The iron ore, carbon and a flux are added to the top of the furnace and hot air is blasted into the bottom of the furnace. A number of reactions occur in the furnace to finally remove the iron from its ore. Iron oxides are reduced by carbon monoxide to produce iron.

- Iron can occur in a number of forms, depending on its level of purity and carbon content. It can also occur in an **alloy** e.g. steel.
- **Phosphates** are found in sedimentary rock, which must be quarried to access the ore.
- Phosphates react with phosphoric acid or sulfuric acid to produce a **superphosphate** ($Ca(H_2PO_4)_2$), which is an important component in **fertilisers**.
- The products of the lithosphere are also important in meeting **energy needs**. **Coal** and **oil** can be extracted from the lithosphere for this purpose.
- Coal and oil are both **fossil fuels**. A fossil fuel is a hydrocarbon that has been formed from the fossilsed remains of plants and animals that have been under conditions of high heat and pressure over a long period of time.
- Coal and oil are **non-renewable resources**, meaning that once they have been used up, no more can be produced.
- Coal can be removed from the ground using **strip mining**, **open cast mining** or **underground mining**.
- Coal is burned to produce energy, which can be used to generate **electricity**. Coal can also be used to produce **liquid fuels** or a **syngas** which can be converted into other useful products for the chemical industry.
- Some of the **environmental impacts** associated with coal mining include landscape scars, spontaneous combustion, acid formation and global warming.
- Oil is also a fossil fuel but it forms in the **oceans**. It can extracted using either **pumping** or **drilling**, depending on the pressure of the oil.
- **Fractional distillation** of oil can be used to make products such as diesel, gasoline and liquid petroleum gas.
- **Cracking** can be used to convert heavy hydrocarbons to light hydrocarbons.
- The **environmental impacts** of oil extraction and use are similar to those for coal.
- In view of the number of environmental impacts associated with the extraction and use of coal and oil, other **alternative energy sources** should be considered. These include nuclear power, biofuels, hydropower and a number of others. All of these alternatives have their own advantages and disadvantages.

Exercise: Summary Exercise

1. Give one word to describe each of the following phrases:
   (a) earth's crust together with the upper layer of the mantle
   (b) a mineral containing silica and oxygen
   (c) an alloy of iron and tin
   (d) a manual technique used to sort gold from other sediments
2. For each of the following questions, choose the *one correct answer* from the list provided.
   (a) One of the main reasons that South Africa's gold industry has been so economically viable is that...
      i. gold panning can be used as an additional method to extract gold
      ii. open cast mining can be used to extract gold reserves
      iii. South Africa's geological history is such that its gold reserves are concentrated in large reefs
      iv. South Africa has large amounts of water to use in mining
   (b) The complete list of reactants in an iron blast furnace is...

  i. carbon and oxygen
  ii. coal, oxygen, iron ore and limestone
  iii. carbon, oxygen and iron ore
  iv. coal, air, iron ore and slag

3. **More profits, more poisons**

   In the last three decades, gold miners have made use of *cyanidation* to recover gold from the ore. Over 99% of gold from ore can be extracted in this way. It allows miners to obtain gold flakes - too small for the eye to see. Gold can also be extracted from the waste of old operations which sometimes leave as much as a third of the gold behind.

   The left-over cyanide can be re-used, but is more often stored in a pond behind a dam or even dumped directly into a local river. A teaspoonful of 2% solution of cyanide can kill a human adult.

   Mining companies insist that cyanide breaks down when exposed to sunlight and oxygen which render it harmless. They also point to scientific studies that show that cyanide swallowed by fish will not 'bio-accumulate', which means it does not pose a risk to anyone who eats the fish. In practice, cyanide solution that seeps into the ground will not break down because of the absence of sunlight. If the cyanide solution is very acidic, it could turn into cyanide gas, which is toxic to fish. On the other hand, if the solution is alkaline the cyanide does not break down.

   There are no reported cases of human death from cyanide spills. If you don't see corpses, everything is okay.

   (a) What is *cyanidation*?
   (b) What type of chemical reaction takes place during this process: precipitation, acid-base or redox?
   (c) Is the pH of the solution after cyanidation greater than, less than or equal to 7?
   (d) How is solid gold recovered from this solution?
   (e) Refer to cyanidation and discuss the meaning of the heading of this extract: *More profits, more poisons.*
   (DoE Grade 11 Paper 2, 2007)

Chapter 22

The Atmosphere - Grade 11

Our earth is truly an amazing planet! Not only is it exactly the right distance from the sun to have temperatures that will support life, but it is also one of the only planets to have liquid water on its surface. In addition, our earth has an atmosphere that has just the right composition to allow life to exist. The **atmosphere** is the layer of gases that surrounds the earth. We may not always be aware of them, but without these gases, life on earth would definitely not be possible. The atmosphere provides the gases that animals and plants need for respiration (breathing) and photosynthesis (the production of food), it helps to keep temperatures on earth constant and also protects us from the sun's harmful radiation.

In this chapter, we are going to take a closer look at the chemistry of the earth's atmosphere and at some of the human activities that threaten the delicate balance that exists in this part of our planet.

22.1 The composition of the atmosphere

Earth's atmosphere is a mixture of gases. Two important gases are nitrogen and oxygen, which make up about 78.1% and 20.9% of the atmosphere respectively. A third gas, Argon, contributes about 0.9%, and a number of other gases such as carbon dioxide, methane, water vapour, helium and ozone make up the remaining 0.1%. In an earlier chapter, we discussed the importance of nitrogen as a component of proteins, the building blocks of life. Similarly, oxygen is essential for life because it is the gas we need for respiration. We will discuss the importance of some of the other gases later in this chapter.

Interesting Fact

The earth's early atmosphere was very different from what it is today. When the earth formed around 4.5 billion years ago, there was probably no atmosphere. Some scientists believe that the earliest atmosphere contained gases such as water vapour, carbon dioxide, nitrogen and sulfur which were released from inside the planet as a result of volcanic activity. Many scientists also believe that the first stage in the evolution of life, around 4 billion years ago, needed an oxygen-free environment. At a later stage, these primitive forms of plant life began to release small amounts of oxygen into the atmosphere as a product of photosynthesis. During photosynthesis, plants use carbon dioxide, water and sunlight to produce simple sugars. Oxygen is also released in the process.

$$6CO_2 + 6H_2O + \text{sunlight} \rightarrow C_6H_{12}O_6 + 6O_2$$

This build-up of oxygen in the atmosphere eventually led to the formation of the ozone layer, which helped to filter the sun's harmful UV radiation so that plants were able to flourish in different environments. As plants became more widespread and photosythesis increased, so did the production of oxygen. The increase in the amount of oxygen in the atmosphere would have allowed more forms of life to exist.

If you have ever had to climb to a very high altitude (altitude means the 'height' in the atmosphere), you will have noticed that it becomes very difficult to breathe, and many climbers suffer from 'altitude sickness' before they reach their destination. This is because the density of gases becomes less as you move higher in the atmosphere. It is **gravity** that holds the atmosphere close to the earth. As you move higher, this force weakens slightly and so the gas particles become more spread out. In effect, when you are at a high altitude, the gases in the atmosphere haven't changed, but there are fewer oxygen molecules in the same amount of air that you are able to breathe.

Definition: Earth's atmosphere
The Earth's atmosphere is a layer of gases that surround the planet, and which are held there by the Earth's gravity. The atmosphere contains roughly 78.1% nitrogen, 20.9% oxygen, 0.9% argon, 0.038% carbon dioxide, trace amounts of other gases, and a variable amount of water vapour. This mixture of gases is commonly known as air. The atmosphere protects life on Earth by absorbing ultraviolet solar radiation and reducing temperature extremes between day and night.

22.2 The structure of the atmosphere

The earth's atmosphere is divided into different layers, each with its own particular characteristics (figure 22.1).

22.2.1 The troposphere

The **troposphere** is the lowest level in the atmosphere, and it is the part in which we live. The troposphere varies in thickness, and extends from the ground to a height of about 7km at the poles and about 18km at the equator. An important characteristic of the troposphere is that its temperature *decreases* with an increase in altitude. In other words, as you climb higher, it will get colder. You will have noticed this if you have climbed a mountain, or if you have moved from a city at a high altitude to one which is lower; the average temperature is often lower where the altitude is higher. This is because the troposphere is heated from the 'bottom up'. In other words, places that are closer to the Earth's surface will be warmer than those at higher altitudes. The heating of the atmosphere will be discussed in more detail later in this chapter.

The word troposphere comes from the Greek *tropos*, meaning *turning* or *mixing*. The troposphere is the most turbulent part of the atmosphere and is the part where our **weather** takes place. Weather is the state of the air at a particular place and time e.g. if it is warm or cold, wet or dry, and how cloudy or windy it is. Generally, jet aircraft fly just above the troposphere to avoid all this turbulence.

22.2.2 The stratosphere

Above the troposphere is another layer called the **stratosphere**, where most long distance aircraft fly. The stratosphere extends from altitudes of 10 to 50km. If you have ever been in an aeroplane and have looked out the window once you are well into the flight, you will have noticed

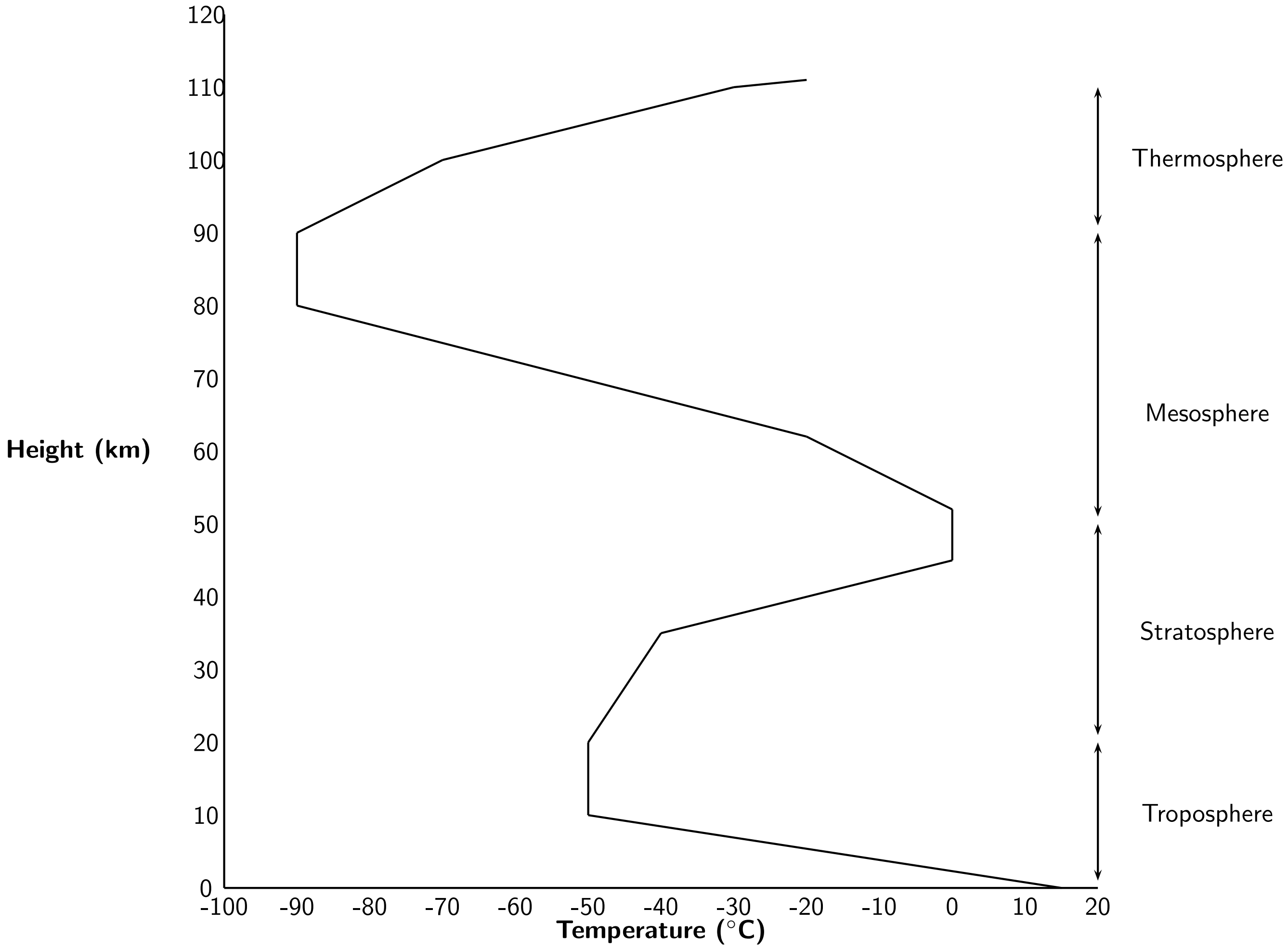


Figure 22.1: A generalised diagram showing the structure of the atmosphere to a height of 110 km

that you are actually flying above the level of the clouds. As we have already mentioned, clouds and weather occur in the troposphere, whereas the stratosphere has very stable atmospheric conditions and very little turbulence. It is easy to understand why aircraft choose to fly here!

The stratosphere is different from the troposphere because its temperature *increases* as altitude increases. This is because the stratosphere absorbs solar radiation directly, meaning that the upper layers closer to the sun will be warmer. The upper layers of the stratosphere are also warmer because of the presence of the **ozone layer**. Ozone (O_3) is formed when solar radiation splits an oxygen molecule (O_2) into two atoms of oxygen. Each individual atom is then able to combine with an oxygen molecule to form ozone. The two reactions are shown below:

$$O_2 \rightarrow O + O$$

$$O + O_2 \rightarrow O_3$$

The change from one type of molecule to another produces energy, and this contributes to higher temperatures in the upper part of the stratosphere. An important function of the ozone layer is to absorb UV radiation and reduce the amount of harmful radiation that reaches the Earth's surface.

Extension: CFCs and the ozone layer

You may have heard people talking about 'the hole in the ozone layer'. What do they mean by this and do we need to be worried about it?

Most of the earth's ozone is found in the stratosphere and this limits the amount of UV radiation that reaches the earth. However, human activities have once again disrupted the chemistry of the atmosphere. Chlorofluorocarbons (CFC's) are compounds found in aerosol cans, fridges and airconditioners. In aerosol cans, it is the CFC's that cause the substance to be sprayed outwards. The bad side of CFC's is that, when they are released into the atmosphere, they break down ozone molecules so that the ozone is no longer able to protect us as much from UV rays. The 'ozone hole' is actually a thinning of the ozone layer approximately above Antarctica. Let's take a closer look at the chemical reactions that are involved in breaking down ozone:

1. When CFC's react with UV radiation, a carbon-chlorine bond in the chlorofluorocarbon breaks and a new compound is formed, with a chlorine atom.

$$CFCl_3 + UV \rightarrow CFCl_2 + Cl$$

2. The single chlorine atom reacts with ozone to form a molecule of chlorine monoxide and oxygen gas. In the process, ozone is destroyed.

$$Cl + O_3 \rightarrow ClO + O_2$$

3. The chlorine monoxide then reacts with a free oxygen atom (UV radiation breaks O_2 down into single oxygen atoms) to form oxygen gas and a single chlorine atom.

$$ClO + O \rightarrow Cl + O_2$$

4. The chlorine atom is then free to attack more ozone molecules, and the process continues. A single CFC molecule can destroy 100 000 ozone molecules.

One possible consequence of ozone depletion is an increase in the incidence of skin cancer because there is more UV radiation reaching earth's surface. CFC replacements are now being used to reduce emissions, and scientists are trying to find ways to restore ozone levels in the atmosphere.

22.2.3 The mesosphere

The mesosphere is located about 50-80/85km above Earth's surface. Within this layer, temperature decreases with increasing altitude. Temperatures in the upper mesosphere can fall as low as -100°C in some areas. Millions of meteors burn up daily in the mesosphere because of collisions with the gas particles that are present in this layer. This leads to a high concentration of iron and other metal atoms.

22.2.4 The thermosphere

The thermosphere exists at altitudes above 80 km. In this part of the atmosphere, ultraviolet (UV) and shorter X-Ray radiation from the sun cause neutral gas atoms to be *ionised*. At these radiation frequencies, photons from the solar radiation are able to dislodge electrons from neutral atoms and molecules during a collision. A *plasma* is formed, which consists of negative free electrons and positive ions. This part of the atmosphere is called the **ionosphere**. At the same time that ionisation takes place however, an opposing process called recombination also begins. Some of the free electrons are drawn to the positive ions, and combine again with them if they are in close enough contact. Since the gas density increases at lower altitudes, the recombination process occurs more often here because the gas molecules and ions are closer together. The ionisation process produces energy which means that the upper parts of the thermosphere, which are dominated by ionisation, have a higher temperature than the lower layers where recombination takes place. Overall, temperature in the thermosphere increases with an increase in altitude.

Extension: The ionosphere and radio waves

The ionosphere is of practical importance because it allows **radio waves** to be transmitted. A radio wave is a type of electromagnetic radiation that humans use to transmit information without wires. When using high-frequency bands, the ionosphere is used to reflect the transmitted radio beam. When a radio wave reaches the ionosphere, the electric field in the wave forces the electrons in the ionosphere into oscillation at the same frequency as the radio wave. Some of the radio wave energy is given up to this mechanical oscillation. The oscillating electron will then either recombine with a positive ion, or will re-radiate the original wave energy back downward again. The beam returns to the Earth's surface, and may then be reflected back into the ionosphere for a second bounce.

The ionosphere is also home to the **auroras**. Auroras are caused by the collision of charged particles (e.g. electrons) with atoms in the earth's upper atmosphere. Charged particles are energised and so, when they collide with atoms, the atoms also become energised. Shortly afterwards, the atoms emit the energy they have gained, as light. Often these emissions are from oxygen atoms, resulting in a greenish glow (wavelength 557.7 nm) and, at lower energy levels or higher altitudes, a dark red glow (wavelength 630 nm). Many other colours can also be observed. For example, emissions from atomic nitrogen are blue, and emissions from molecular nitrogen are purple. Auroras emit visible light (as described above), and also infra-red, ultraviolet and x-rays, which can be observed from space.

Exercise: The composition of the atmosphere

1. Complete the following summary table by providing the missing information for each layer in the atmosphere.

Atmospheric layer	Height (km)	Gas composition	General characteristics
Troposphere	0-18		Turbulent; part of atmosphere where weather occurs
			Ozone reduces harmful radiation reaching Earth
Mesosphere			High concentration of metal atoms
	more than 80 km		

2. Use your knowledge of the atmosphere to explain the following statements:

(a) Athletes who live in coastal areas need to acclimatise if they are competing at high altitudes.
(b) Higher incidences of skin cancer have been recorded in areas where the ozone layer in the atmosphere is thin.
(c) During a flight, turbulence generally decreases above a certain altitude.

22.3 Greenhouse gases and global warming

22.3.1 The heating of the atmosphere

As we mentioned earlier, the distance of the earth from the sun is not the only reason that temperatures on earth are within a range that is suitable to support life. The composition of the atmosphere is also critically important.

The earth receives electromagnetic energy from the sun in the *visible spectrum*. There are also small amounts of infrared and ultraviolet radiation in this incoming solar energy. Most of the radiation is *shortwave* radiation, and it passes easily through the atmosphere towards the earth's surface, with some being reflected before reaching the surface. At the surface, some of the energy is absorbed, and this heats up the earth's surface. But the situation is a little more complex than this.

A large amount of the sun's energy is re-radiated from the surface back into the atmosphere as **infrared** radiation, which is invisible. As this radiation passes through the atmosphere, some of it is absorbed by **greenhouse gases** such as carbon dioxide, water vapour and methane. These gases are very important because they re-emit the energy back towards the surface. By doing this, they help to warm the lower layers of the atmosphere even further. It is this 're-emission' of heat by greenhouse gases, combined with surface heating and other processes (e.g. conduction and advection) that maintain temperatures at exactly the right level to support life. Without the presence of greenhouse gases, most of the sun's energy would be lost and the Earth would be a lot colder than it is! A simplified diagram of the heating of the atmosphere is shown in figure 22.2.

22.3.2 The greenhouse gases and global warming

Many of the greenhouse gases occur naturally in small quantities in the atmosphere. However, human activities have greatly increased their concentration, and this has led to a lot of concern about the impact that this could have in *increasing* global temperatures. This phenomenon is known as **global warming**. Because the natural concentrations of these gases are low, even a small increase in their concentration as a result of human emissions, could have a big effect on temperature. But before we go on, let's look at where some of these human gas emissions come from.

- **Carbon dioxide** (CO_2)

  Carbon dioxide enters the atmosphere through the burning of fossil fuels (oil, natural gas, and coal), solid waste, trees and wood products, and also as a result of other chemical reactions (e.g. the manufacture of cement). Carbon dioxide can also be *removed* from the atmosphere when it is absorbed by plants during photosynthesis.

- **Methane** (CH_4)

  Methane is emitted when coal, natural gas and oil are produced and transported. Methane emissions can also come from livestock and other agricultural practices and from the decay of organic waste.

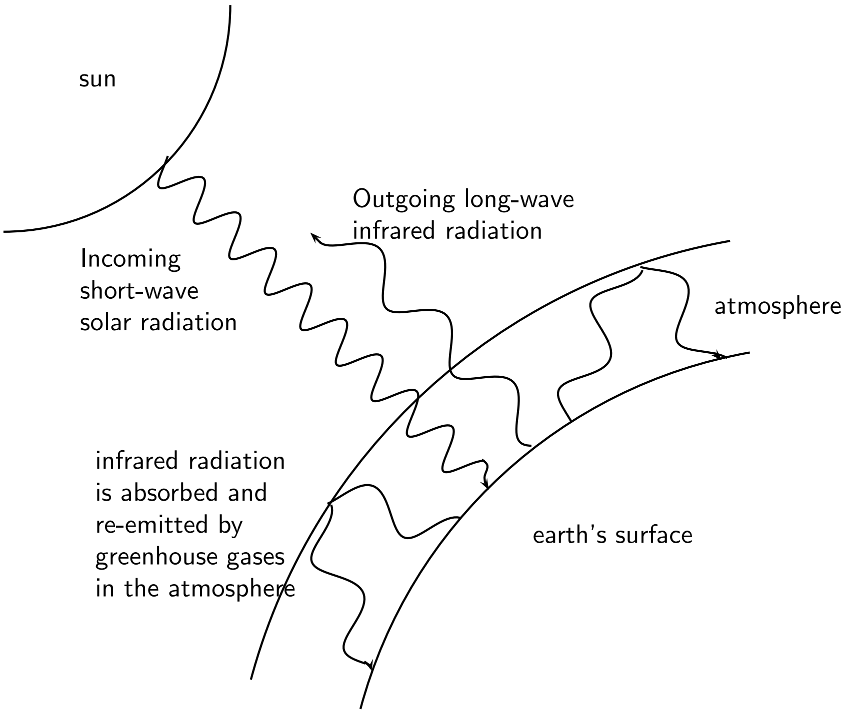


Figure 22.2: The heating of the Earth's atmosphere

- **Nitrous oxide** (N_2O)

  Nitrous oxide is emitted by agriculture and industry, and when fossil fuels and solid waste are burned.

- **Fluorinated gases** (e.g. hydrofluorocarbons, perfluorocarbons, and sulfur hexafluoride)

  These gases are all *synthetic*, in other words they are man-made. They are emitted from a variety of industrial processes. Fluorinated gases are sometimes used in the place of other ozone-depleting substances (e.g. CFC's). These are very powerful greenhouse gases, and are sometimes referred to as High Global Warming Potential gases ('High GWP gases').

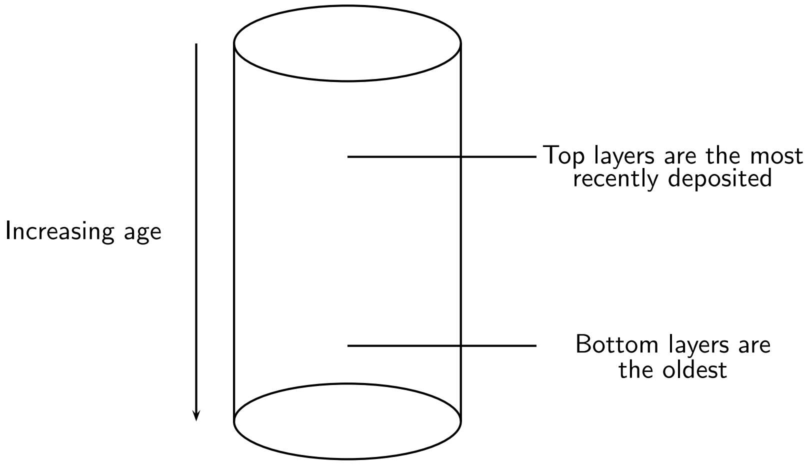
Overpopulation is a major problem in reducing greenhouse gas emissions, and in slowing down global warming. As populations grow, their demands on resources (e.g. energy) increase, and so does their production of greenhouse gases.

Extension: Ice core drilling - Taking a look at earth's past climate

Global warming is a very controversial issue. While many people are convinced that the increase in average global temperatures is directly related to the increase in atmospheric concentrations of carbon dioxide, others argue that the climatic changes we are seeing are part of a natural pattern. One way in which scientists are able to understand what is happening at present, is to understand the earth's *past* atmosphere, and the factors that affected its temperature.

So how, you may be asking, do we know what the earth's *past* climate was like? One method that is used is **ice core drilling**. Antarctica is the coldest continent on earth, and because of this there is very little melting that takes place. Over thousands of years, ice has accumulated in layers and has become more and more compacted as new ice is added. This is partly why Antarctica is also on average one of the *highest* continents! On average, the ice sheet that covers Antarctica is 2500 m thick, and at its deepest location, is 4700 m thick.

As the snow is deposited on top of the ice sheet each year, it traps different chemicals and impurities which are dissolved in the ice. The ice and impurities hold information about the Earth's environment and climate at the time that the ice was deposited. Drilling an ice core from the surface down, is like taking a journey back in time. The deeper into the ice you venture, the older the layer of ice. By analysing the gases and oxygen isotopes that are present (along with many other techniques) in the ice at various points in the earth's history, scientists can start to piece together a picture of what the earth's climate must have been like.



One of the most well known ice cores was the one drilled at a Russian station called **Vostok** in central Antarctica. So far, data has been gathered for dates as far back as 160 000 years!

Activity :: Case Study : Looking at past climatic trends

Make sure that you have read the 'Information box' on ice core drilling before you try this activity.

The values in the table below were extrapolated from data obtained by scientists studying the Vostok ice core. 'Local temperature change' means by how much the temperature at that time was different from what it is today. For example, if the local temperature change 160 000 years ago was -9°C, this means that atmospheric temperatures at that time were 9°C *lower* than what they are today. 'ppm' means 'parts per million' and is a unit of measurement for gas concentrations.

Years before present (x 1000)	Local temperature change (°C)	Carbon dioxide (ppm)
160	-9	190
150	-10	205
140	-10	240
130	-3	280
120	+1	278
110	-4	240
100	-8	225
90	-5	230
80	-6	220
70	-8	250
60	-9	190
50	-7	220
40	-8	180
30	-7	225
20	-9	200
10	-2	260
0 (1850)	-0.5	280
Present		371

Questions

1. On the same set of axes, draw graphs to show how temperature and carbon dioxide concentrations have changed over the last 160 000 years. Hint: 'Years before present' will go on the x-axis, and should be given *negative* values.
2. Compare the graphs that you have drawn. What do you notice?
3. Is there a relationship between temperature and the atmospheric concentration of carbon dioxide?
4. Do these graphs *prove* that temperature changes are determined by the concentration of gases such as carbon dioxide in the atmosphere? Explain your answer.
5. What other factors might you need to consider when analysing climatic trends?

22.3.3 The consequences of global warming

Activity :: Group Discussion : The impacts of global warming
In groups of 3-4, read the following extracts and then answer the questions that follow.

By 2050 Warming to Doom Million Species, Study Says

By 2050, rising temperatures exacerbated by human-induced belches of carbon dioxide and other greenhouse gases could send more than a million of Earth's land-dwelling plants and animals down the road to extinction, according to a recent study. "Climate change now represents at least as great a threat to the number of species surviving on Earth as habitat-destruction and modification," said Chris Thomas, a conservation biologist at the University of Leeds in the United Kingdom.

The researchers worked independently in six biodiversity-rich regions around the world, from Australia to South Africa, plugging field data on species distribution and regional climate into computer models that simulated the ways species' ranges are expected to move in response to temperature and climate changes. According to the researchers' collective results, the predicted range of climate change by 2050 will place 15 to 35 percent of the 1 103 species studied at risk of extinction.

National Geographic News, 12 July 2004

Global Warming May Dry Up Africa's Rivers, Study Suggests

Many climate scientists already predict that less rain will fall annually in parts of Africa within 50 years due to global warming. Now new research suggests that even a small decrease in rainfall on the continent could cause a drastic reduction in river water, the lifeblood for rural populations in Africa.

A decrease in water availability could occur across about 25 percent of the continent, according to the new study. Hardest hit would be areas in northwestern and southern Africa, with some of the most serious effects striking large areas of Botswana and South Africa.

To predict future rainfall, the scientists compared 21 of what they consider to be the best climate change models developed by research teams around the world. On average, the models forecast a 10 to 20% drop in rainfall in northwestern and southern Africa by 2070. With a 20% decrease, Cape Town would be left with just 42% of its river water, and "Botswana would completely dry up," de Wit said. In parts of northern Africa, river water levels would drop below 50%.

Less river water would have serious implications not just for people but for the many animal species whose habitats rely on regular water supplies.

National Geographic News, 3 March 2006

Discussion questions

1. What is meant by 'biodiversity'?
2. Explain why global warming is likely to cause a *loss of biodiversity*.
3. Why do you think a loss of biodiversity is of such concern to conservationists?
4. Suggest some plant or animal species in South Africa that you think might be particularly vulnerable to extinction if temperatures were to rise significantly. Explain why you chose these species.
5. In what way do people, animals and plants rely on river water?
6. What effect do you think a 50% drop in river water level in some parts of Africa would have on the people living in these countries?
7. Discuss some of the other likely impacts of global warming that we can expect (e.g. sea level rise, melting of polar ice caps, changes in ocean currents).

22.3.4 Taking action to combat global warming

Global warming is a major concern at present. A number of organisations, panels and research bodies have been working to gather accurate and relevant information so that a true picture of our current situation can be painted. One important orgaisation that you may have heard of is the **Intergovernmental Panel on Climate Change** (IPCC). The IPCC was established in 1988 by two United Nations organizations, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), to evaluate the risk of climate change brought on by humans. You may also have heard of the **Kyoto Protocol**, which will be discussed a little later.

Activity :: Group Discussion : World carbon dioxide emissions

The data in the table below shows carbon dioxide emissions from the consumption of fossil fuels (in million metric tons of carbon dioxide).

Region or Country	1980	1985	1990	1995	2000	2004
United States	4754	4585	5013	5292	5815	5912
Brazil	186	187	222	288	345	336
France	487	394	368	372	399	405
UK	608	588	598	555	551	579
Saudi Arabia	175	179	207	233	288	365
Botswana	1.26	1.45	2.68	3.44	4.16	3.83
South Africa	234	298	295	344	378	429
India	299	439	588	867	1000	1112
World Total	18333	19412	21426	22033	23851	27043

Questions

1. Using a coloured pen, highlight those countries that are 'developed' and those that are 'developing'.
2. Explain why CO_2 emissions are so much higher in developed countries than in developing countries.
3. How does South Africa compare to the other developing countries, and also to the developed countries?

Carbon dioxide emissions are a major problem worldwide. The **Kyoto Protocol** was signed in Kyoto, Japan in December 1997. Its main objective was to reduce global greenhouse gas emissions by encouraging countries to become signatories to the guidelines that had been laid out in the protocol. These guidelines set targets for the world's major producers to reduce their emissions within a certain time. However, some of the worst contributors to greenhouse gas emissions (e.g. USA) were not prepared to sign the protocol, partly because of the potential effect this would have on the country's economy, which relies on industry and other 'high emission' activities.

Panel discussion

Form groups with 5 people in each. Each person in the group must adopt one of the following roles during the discussion:

- the owner of a large industry
- an environmental scientist
- an economist
- a politician
- a chairperson for the discussion

In your group, you are going to discuss some of the economic and environmental implications for a country that decides to sign the Kyoto Protocol. Each person will have the opportunity to express the view of the character they have adopted. You may ask questions of the other people, or challenge their ideas, provided that you ask permission from the chairperson first.

22.4 Summary

- The **atmosphere** is the layer of gases that surrounds Earth. These gases are important in sustaining life, regulating temperature and protecting Earth from harmful radiation.
- The gases that make up the atmosphere are nitrogen, oxygen, carbon dioxide and others e.g. water vapour, methane.
- There are four layer in the atmosphere, each with their own characteristics.

- The **troposphere** is the lowest layer and here, temperature decreases with an increase in altitude. The troposphere is where weather occurs.

- The next layer is the **stratosphere** where temperature increases with an increase in altitude because of the presence of ozone in this layer, and the direct heating from the sun.

- The depletion of the ozone layer is largely because of CFC's, which break down ozone through a series of chemical reactions.

- The **mesosphere** is characterised by very cold temperatures and meteor collisions. The mesosphere contains high concentrations of metal atoms.

- In the **thermosphere**, neutral atoms are ionised by UV and X-ray radiation from the sun. Temperature increases with an increase in altitude because of the energy that is released during this ionisation process, which occurs mostly in the upper thermosphere.

- The thermosphere is also known as the **ionosphere**, and is the part of the atmosphere where radio waves can be transmitted.

- The **auroras** are bright coloured skies that occur when charged particles collide with atoms in the upper atmosphere. Depending on the type of atom, energy is released as light at different wavelengths.

- The Earth is heated by radiation from the sun. Incoming radiation has a short wavelength and some is absorbed directly by the Earth's surface. However, a large amount of energy is re-radiated as longwave infrared radiation.

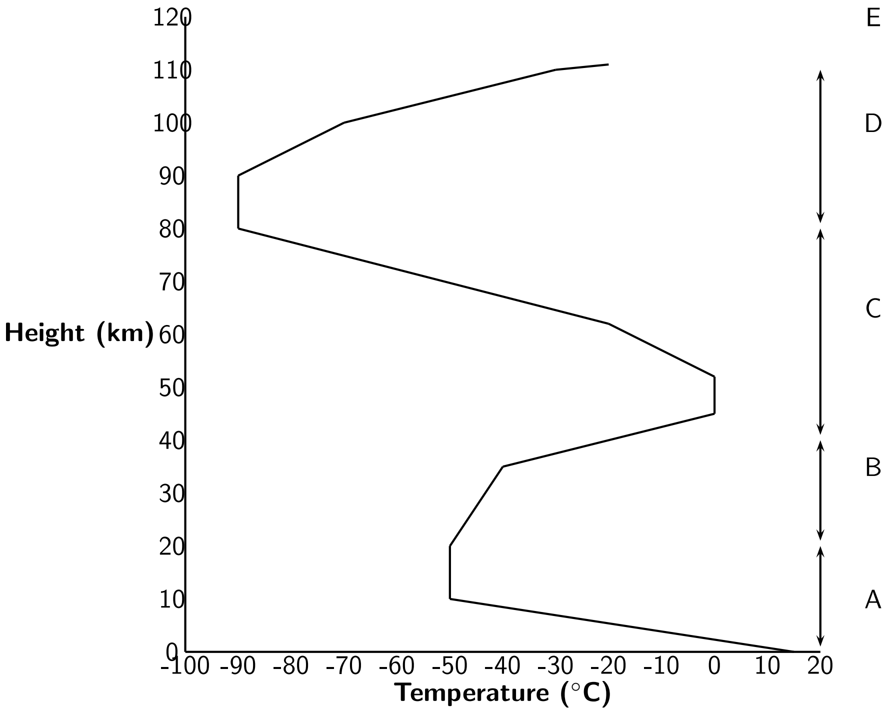
- **Greenhouse gases** such as carbon dioxide, water vapour and methane absorb infrared radiation and re-emit it back towards the Earth's surface. In this way, the bottom layers of the atmsophere are kept much warmer than they would be if all the infrared radiation was lost.

- Human activities such as the burning of fossil fuels, increase the concentration of greenhouse gases in the atmosphere and may contribute towards **global warming**.

- Some of the impacts of global warming include changing climate patterns, rising sea levels and a loss of biodiversity, to name a few. Interventions are needed to reduce this phenomenon.

Exercise: Summary Exercise

1. The atmosphere is a relatively thin layer of gases which support life and provide protection to living organisms. The force of gravity holds the atmosphere against the earth. The diagram below shows the temperatures associated with the various layers that make up the atmosphere and the altitude (height) from the earth's surface.



(a) Write down the names of the layers A, B and D of the atmosphere.

(b) In which one of the layers of the atmosphere is ozone found?

(c) Give an explanation for the decrease in temperature as altitude increases in layer A.

(d) In layer B, there is a steady increase in temperature as the altitude increases. Write down an explanation for this trend.

2. **Planet Earth in Danger**

It is now accepted that greenhouse gases are to blame for planet earth getting warmer. The increase in the number of sudden floods in Asia and droughts in Africa; the rising sea level and increasing average temperatures are global concerns. Without natural greenhouse gases,like carbon dioxide and water vapour,life on earth is not possible. However, the increase in levels of carbon dioxide in the atmosphere since the Industrial Revolution is of great concern. Greater disasters are to come, which will create millions of climate refugees. It is our duty to take action for the sake of future generations who will pay dearly for the wait-and-see attitude of the current generation. Urgent action to reduce waste is needed. Global warming is a global challenge and calls for a global response now, not later.

(Adapted from a speech by the French President, Jacques Chirac)

(a) How do greenhouse gases, such as carbon dioxide, heat up the earth's surface?

(b) Draw a Lewis structure for the carbon dioxide molecule

(c) The chemical bonds within the carbon dioxide molecule are polar. Support this statement by performing a calculation using the table of electronegativities.

(d) Classify the carbon dioxide molecule as polar or non-polar. Give a reason for your answer.

(e) Suggest ONE way in which YOU can help to reduce the emissions of greenhouse gases.

3. Plants need carbon dioxide (CO_2) to manufacture food. However, the engines of motor vehicles cause too much carbon dioxide to be released into the atmosphere.

(a) State the possible consequence of having too much carbon dioxide in the atmosphere.

(b) Explain **two** possible effects on humans if the amount of carbon dioxide in the atmosphere becomes too low.

(DoE Exemplar Paper Grade 11, 2007)

Chapter 23

The Chemical Industry - Grade 12

23.1 Introduction

The chemical industry has been around for a very long time, but not always in the way we think of it today! Dyes, perfumes, medicines and soaps are all examples of products that have been made from chemicals that are found in either plants or animals. However, it was not until the time of the Industrial Revolution that the chemical industry as we know it today began to develop. At the time of the Industrial Revolution, the human population began to grow very quickly and more and more people moved into the cities to live. With this came an increase in the need for things like paper, glass, textiles and soaps. On the farms, there was a greater demand for fertilisers to help produce enough food to feed all the people in cities and rural areas. Chemists and engineers responded to these growing needs by using their technology to produce a variety of new chemicals. This was the start of the chemical industry.

In South Africa, the key event that led to the growth of the chemical industry was the discovery of diamonds and gold in the late 1800's. Mines needed explosives so that they could reach the diamonds and gold-bearing rock, and many of the main chemical companies in South Africa developed to meet this need for explosives. In this chapter, we are going to take a closer look at one of South Africa's major chemical companies, **Sasol**, and will also explore the **chloralkali** and **fertiliser** industries.

23.2 Sasol

Oil and natural gas are important fuel resources. Unfortunately, South Africa has no large oil reserves and, until recently, had very little natural gas. One thing South Africa *does* have however, is large supplies of **coal**. Much of South Africa's chemical industry has developed because of the need to produce oil and gas from coal, and this is where Sasol has played a very important role.

Sasol was established in 1950, with its main aim being to convert low grade coal into petroleum (crude oil) products and other chemical feedstocks. A 'feedstock' is something that is used to make another product. Sasol began producing oil from coal in 1955.

The first interest in coal chemistry started as early as the 1920's. In the early 1930's a research engineer called Etienne Rousseau was employed to see whether oil could be made from coal using a new German technology called the **Fischer-Tropsch** process. After a long time, and after many negotiations, Rousseau was given the rights to operate a plant using this new process. As a result, the government-sponsored 'South African Coal, Oil and Gas Corporation Ltd' (commonly called 'Sasol') was formed in 1950 to begin making oil from coal. A manufacturing plant was established in the Free State and the town of **Sasolburg** developed around this plant. Production began in 1955. In 1969, the **Natref** crude oil refinery was established, and by 1980 and 1982 Sasol Two and Sasol Three had been built at **Secunda**.

23.2.1 Sasol today: Technology and production

Today, Sasol is an oil and gas company with diverse chemical interests. Sasol has three main areas of operation: Firstly, **coal to liquid fuels technology**, secondly the production of **crude oil** and thirdly the conversion of **natural gas to liquid fuel**.

1. **Coal to liquid fuels**

   Sasol is involved in mining coal and converting it into synthetic fuels, using the **Fischer-Tropsch** technology. Figure 23.1 is a simplified diagram of the process that is involved.

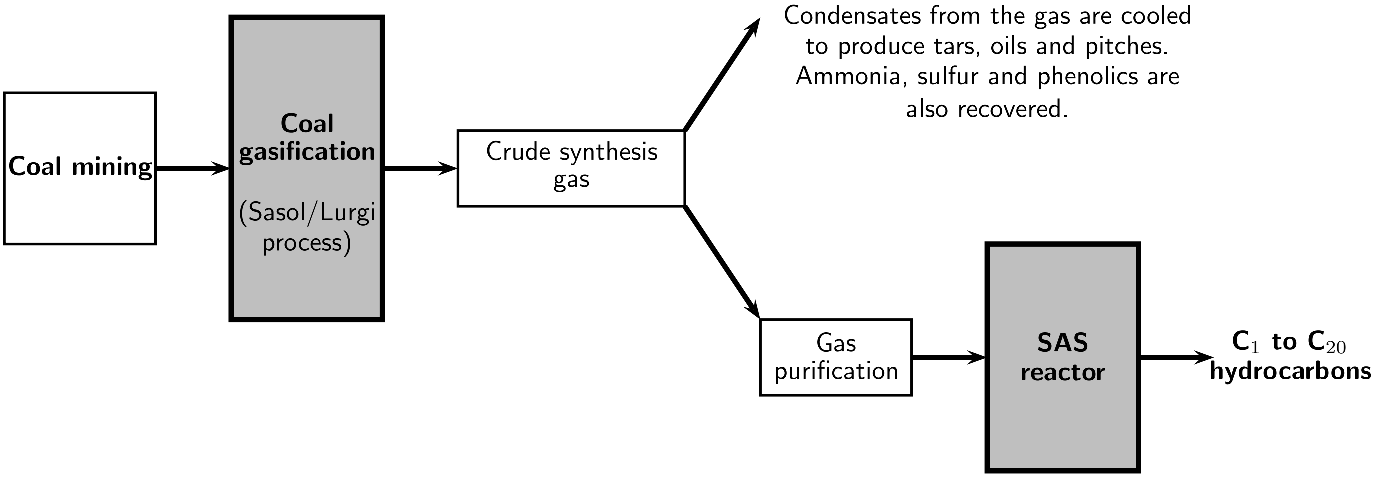


Figure 23.1: The gasification of coal to produce liquid fuels

Coal gasification is also known as the **Sasol/Lurgi** gasification process, and involves converting low grade coal to a synthesis gas. Low grade coal has a low percentage carbon, and contains other impurities. The coal is put under extremely high pressure and temperature in the presence of steam and oxygen. The gas that is produced has a high concentration of hydrogen (H_2) and carbon monoxide (CO). That is why it is called a 'synthesis gas', because it is a mixture of more than one gas.

In the **Sasol Advanced Synthol (SAS) reactors**, the gas undergoes a high temperature Fischer-Tropsch conversion. Hydrogen and carbon monoxide react under high pressure and temperature and in the presence of an iron catalyst, to produce a range of hydrocarbon products. Below is the generalised equation for the process. Don't worry too much about the numbers that you see in front of the reactants and products. It is enough just to see that the reaction of hydrogen and carbon monoxide (the two gases in the *synthesis gas*) produces a hydrocarbon and water.

$$(2n + 1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O$$

A range of hydrocarbons are produced, including petrol, diesel, jet fuel, propane, butane, ethylene, polypropylene, alcohols and acetic acids.

Important: Different types of fuels

It is important to understand the difference between types of fuels and the terminology that is used for them. The table below summarises some of the fuels that will be mentioned in this chapter.

Compound	Description
Petroleum (crude oil)	A naturally occurring liquid that forms in the earth's lithosphere (see section 21.9 in chapter 21). It is a mixture of hydrocarbons, mostly alkanes, ranging from C_5H_{12} to $C_{18}H_{38}$.
Natural gas	Natural gas has the same origin as petroleum, but is made up of shorter hydrocarbon chains.
Paraffin wax	This is made up of longer hydrocarbon chains, making it a solid compound.
Petrol (gasoline)	A liquid fuel that is derived from petroleum, but which contains extra additives to increase the octane rating of the fuel. Petrol is used as a fuel in combustion engines.
Diesel	Diesel is also derived from petroleum, but is used in diesel engines.
Liquid Petroleum Gas (LPG)	LPG is a mixture of hydrocarbon gases, and is used as a fuel in heating appliances and vehicles. Some LPG mixtures contain mostly propane, while others are mostly butane. LPG is manufactured when crude oil is refined, or is extracted from natural gas supplies in the ground.
Paraffin	This is a technical name for the alkanes, but refers specifically to the *linear* alkanes. *Isoparaffin* refers to non-linear alkanes.
Jet fuel	A type of aviation fuel designed for use in jet engined aircraft. It is an oil-based fuel and contains additives such as antioxidants, corrosion inhibitors and icing inhibitors.

You will notice in the diagram that Sasol doesn't only produce liquid fuels, but also a variety of other chemical products. Sometimes it is the synthetic fuels themselves that are used as feedstocks to produce these chemical products. This is done through processes such as **hydrocracking** and **steamcracking**. Cracking is when heavy hydrocarbons are converted to simpler light hydrocarbons (e.g. LPG and petrol) through the breaking of C-C bonds. A heavy hydrocarbon is one that has a high number of hydrogen and carbon atoms (more solid), and a light hydrocarbon has fewer hydrogen and carbon atoms and is either a liquid or a gas.

Definition: Hydrocracking

Hydrocracking is a cracking process that is assisted by the presence of an elevated partial pressure of hydrogen gas. It produces chemical products such as ethane, LPG, isoparaffins, jet fuel and diesel.

Definition: Steam cracking
Steam cracking occurs under very high temperatures. During the process, a liquid or gaseous hydrocarbon is diluted with steam and then briefly heated in a furnace at a temperature of about 850^0C. Steam cracking is used to convert *ethane* to *ethylene*. Ethylene is a chemical that is needed to make plastics. Steam cracking is also used to make propylene, which is an important fuel gas.

2. **Production of crude oil**

Sasol obtains crude oil off the coast of Gabon (a country in West Africa) and refines this at the Natref refinery (figure 23.2). Sasol also sells liquid fuels through a number of service stations.

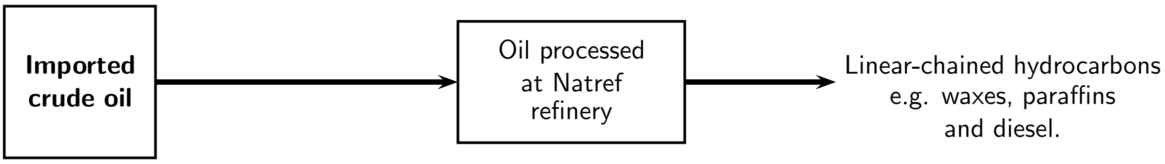


Figure 23.2: Crude oil is refined at Sasol's Natref refinery to produce liquid fuels

3. **Liquid fuels from natural gas**

Sasol produces natural gas in Mozambique and is expanding its 'gas to fuel' technology. The gas undergoes a complex process to produce linear-chained hydrocarbons such as waxes and paraffins (figure 23.3).

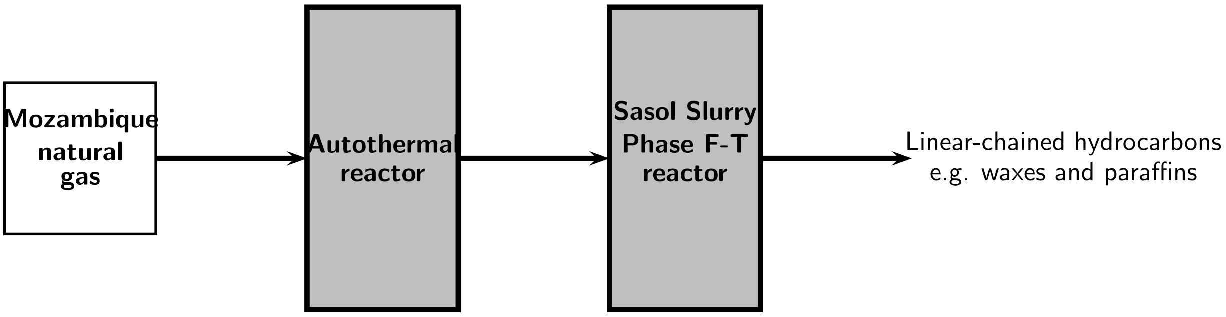


Figure 23.3: Conversion of natural gas to liquid fuels

In the **autothermal reactor**, methane from natural gas reacts with steam and oxygen over an iron-based catalyst to produce a *synthesis gas*. This is a similar process to that involved in coal gasification. The oxygen is produced through the **fractional distillation of air**.

Definition: Fractional distillation
Fractional distillation is the separation of a mixture into its component parts, or fractions. Since air is made up of a number of gases (with the major component being nitrogen), fractional distillation can be used to separate it into these different parts.

The syngas is then passes through a **Sasol Slurry Phase Distillate (SSPD)** process. In this process, the gas is reacted at far lower temperatures than in the SAS reactors. Apart from hard wax and candle wax, high quality diesel can also be produced in this process. Residual gas from the SSPD process is sold as pipeline gas while some of the lighter hydrocarbons are treated to produce kerosene and paffin. Ammonia is also produced, which can be used to make fertilisers.

Interesting Fact

Sasol is a major player in the emerging Southern African natural gas industry, after investing 1.2 billion US dollars to develop onshore gas fields in central Mozambique. Sasol has been supplying natural gas from Mozambique's Temane field to customers in South Africa since 2004.

Exercise: Sasol processes

Refer to the diagrams summarising the three main Sasol processes, and use these to answer the following questions:

1. Explain what is meant by each of the following terms:
    (a) crude oil
    (b) hydrocarbon
    (c) coal gasification
    (d) synthetic fuel
    (e) chemical feedstock
2. (a) What is diesel?
    (b) Describe two ways in which diesel can be produced.
3. Describe one way in which lighter chemical products such as ethylene, can be produced.
4. Coal and oil play an important role in Sasol's technology.
    (a) In the table below, summarise the similarities and differences between coal, oil and natural gas in terms of how they are formed ('origin'), their general chemical formula and whether they are solid, liquid or gas.

	Coal	Oil	Natural gas
Origin			
General chemical formula			
Solid, liquid or gas			

    (b) In your own words, describe how coal is converted into liquid fuels.
    (c) Explain why Sasol's 'coal to liquid fuels' technology is so important in meeting South Africa's fuel needs.
    (d) Low grade coal is used to produce liquid fuels. What is the main use of higher grade coal in South Africa?

Activity :: Case Study : Safety issues and risk assessments

Safety issues are important to consider when dealing with industrial processes. Read the following extract that appeared in the Business report on 6th February 2006, and then discuss the questions that follow.

> Cape Town - Sasol, the petrochemicals group, was likely to face prosecution on 10 charges of culpable homicide after an explosion at its Secunda plant in 2004 in which 10 people died, a Cape Town labour law specialist said on Friday. The specialist, who did not want to be named, was speaking after the inquiry into the explosion was concluded last Tuesday. It was convened by the labour department.
>
> The evidence led at the inquiry showed a failure on the part of the company to conduct a proper risk assessment and that: Sasol failed to identify hazards associated with a high-pressure gas pipeline running through the plant, which had been shut for extensive maintenance work, in the presence of hundreds of people and numerous machines, including cranes, fitters, contractors, and welding and cutting machines. Because there had never been a risk assessment, the hazard of the high-pressure pipeline had never been identified.
>
> Because Sasol had failed to identify the risk, it did not take any measures to warn people about it, mark the line or take precautions. There had also been inadequacy in planning the shutdown work. In the face of a barrage of criticism for the series of explosions that year, Sasol embarked on a comprehensive programme to improve safety at its operations and appointed Du Pont Safety Resources, the US safety consultancy, to benchmark the petrochemical giant's occupational health and safety performance against international best practice.

1. Explain what is meant by a 'risk assessment'.
2. Imagine that you have been asked to conduct a risk assessment of the Sasol/Lurgi gasification process. What information would you need to know in order to do this assessment?
3. In groups, discuss the importance of each of the following in ensuring the safety of workers in the chemical industry:
   - employing experienced Safety, Health and Environment personnel
   - regular training to identify hazards
   - equipment maintenance and routine checks
4. What other precautions would you add to this list to make sure that working conditions are safe?

23.2.2 Sasol and the environment

From its humble beginnings in 1950, Sasol has grown to become a major contributor towards the South African economy. Today, the industry produces more than 150 000 barrels of fuels and petrochemicals per day, and meets more than 40% of South Africa's liquid fuel requirements. In total, more than 200 fuel and chemical products are manufactured at Sasolburg and Secunda, and these products are exported to over 70 countries worldwide. This huge success is largely due to Sasol's ability to diversify its product base. The industry has also helped to provide about 170 000 jobs in South Africa, and contributes around R40 billion to the country's Gross Domestic Product (GDP).

However, despite these obvious benefits, there are always environmental costs associated with industry. Apart from the vast quantities of resources that are needed in order for the industry to operate, the production process itself produces waste products and pollutants.

Exercise: Consumption of resources

Any industry will always use up huge amounts of resources in order to function effectively, and the chemical industry is no exception. In order for an industry to operate, some of the major resources that are needed are **energy** to drive many of the processes, **water**, either as a coolant or as part of a process and **land** for mining or operations.

Refer to the data table below which shows Sasol's water use between 2002 and 2005 (*Sasol Sustainable Development Report 2005*), and answer the questions that follow.

Water use $(1000m^3)$	2002	2003	2004	2005
River water	113 722	124 179	131 309	124 301
Potable water	15 126	10 552	10 176	10 753
Total	**157 617**	**178 439**	**173 319**	**163 203**

1. Explain what is meant by 'potable' water.
2. Describe the trend in Sasol's water use that you see in the above statistics.
3. Suggest possible reasons for this trend.
4. List some of the environmental impacts of using large amounts of river water for industry.
5. Suggest ways in which these impacts could be reduced

Exercise: Industry and the environment

Large amounts of gases and pollutants are released during production, and when the fuels themselves are used. Refer to the table below, which shows greenhouse gas and atmospheric pollution data for Sasol between 2002 and 2005, and then answer the questions that follow. (*Source: Sasol Sustainable Development Report 2005*)

Greenhouse gases and air pollutants (kilotonnes)	2002	2003	2004	2005
Carbon dioxide (CO_2)	57 476	62 873	66 838	60 925
Hydrogen sulfide (H_2S)	118	105	102	89
Nitrogen oxides (NO_x)	168	173	178	166
Sulfur dioxide (SO_2)	283	239	261	222

1. Draw line graphs to show how the quantity of each pollutant produced has changed between 2002 and 2005.
2. Describe what you see in the graphs, and suggest a reason for this trend.
3. Explain what is meant by each of the following terms:
   (a) greenhouse gas
   (b) global warming
4. Describe some of the possible effects of global warming.
5. When sulfur dioxide is present in the atmosphere, it may react with water vapour to produce weak *sulfuric acid*. In the same way, nitrogen dioxide and water vapour react to form *nitric acid*. These reactions in the atmosphere may cause **acid rain**. Outline some of the possible consequences of acid rain.
6. Many industries are major contributors towards environmental problems such as global warming, environmental pollution, over-use of resources and acid rain. Industries are in a difficult position: On one hand they must meet the ever increasing demands of society, and on the other, they must achieve this with as little environmental impact as possible. This is a huge challenge.

- Work in groups of 3-4 to discuss ways in which industries could be encouraged (or in some cases forced) to reduce their environmental impact.
- Elect a spokesperson for each group, who will present your ideas to the class.
- Are the ideas suggested by each group practical?
- How easy or difficult do you think it would be to implement these ideas in South Africa?

Sasol is very aware of its responsibility towards creating cleaner fuels. From 1st January 2006, the South African government enforced a law to prevent lead from being added to petrol. Sasol has complied with this. One branch of Sasol, **Sasol Technology** also has a bio-diesel research and development programme focused on developing more environmentally friendly forms of diesel. One way to do this is to use renewable resources such as soybeans to make diesel. Sasol is busy investigating this new technology.

23.3 The Chloralkali Industry

The chlorine-alkali (chloralkali) industry is an important part of the chemical industry, and produces **chlorine** and **sodium hydroxide** through the electrolysis of salt (NaCl). The main raw material is **brine** which is a saturated solution of sodium chloride (NaCl) that is obtained from natural salt deposits.

The products of this industry have a number of important uses. **Chlorine** is used to purify water, and is used as a disinfectant. It is also used in the manufacture of many every-day items such as hypochlorous acid, which is used to kill bacteria in drinking water. Chlorine is also used in paper production, antiseptics, food, insecticides, paints, petroleum products, plastics (such as polyvinyl chloride or PVC), medicines, textiles, solvents, and many other consumer products. Many chemical products such as chloroform and carbon tetrachloride also contain chlorine.

Sodium hydroxide (also known as 'caustic soda') has a number of uses, which include making soap and other cleaning agents, purifying bauxite (the ore of aluminium), making paper and making rayon (artificial silk).

23.3.1 The Industrial Production of Chlorine and Sodium Hydroxide

Chlorine and sodium hydroxide can be produced through a number of different reactions. However, one of the problems is that when chlorine and sodium hydroxide are produced together, the chlorine combines with the sodium hydroxide to form chlorate (ClO^-) and chloride (Cl^-) ions. This produces sodium chlorate, NaClO, a component of household bleach. To overcome this problem the chlorine and sodium hydroxide must be separated from each other so that they don't react. There are three industrial processes that have been designed to overcome this problem, and to produce chlorine and sodium hydroxide. All three methods involve **electrolytic cells** (chapter 17).

Important: Electrolytic cells

Electrolytic cells are used to split up or loosen ions. They are made up of an **electrolyte** and two electrodes, the **cathode** and the **anode**. An electrolytic cell is activated by applying an external electrical current. This creates an electrical potential across the cathode and anode, and forces a chemical reaction to take place in the electrolyte. Cations flow towards the cathode and are reduced. Anions flow to the anode and are oxidised. Two new products are formed, one product at the cathode and one at the anode.

1. **The Mercury Cell**

   In the mercury-cell (figure 23.4), brine passes through a chamber which has a carbon electrode (the anode) suspended from the top. Mercury flows along the floor of this chamber and acts as the cathode. When an electric current is applied to the circuit, chloride ions in the electrolyte are oxidised to form chlorine gas.

   $$2\mathrm{Cl}^-_{(aq)} \rightarrow \mathrm{Cl}_{2(g)} + 2\mathrm{e}^-$$

   At the cathode, sodium ions are reduced to sodium.

   $$2\mathrm{Na}^+_{(aq)} + 2\mathrm{e}^- \rightarrow 2\mathrm{Na}_{(Hg)}$$

   The sodium dissolves in the mercury, forming an amalgam of sodium and mercury. The amalgam is then poured into a separate vessel, where it decomposes into sodium and mercury. The sodium reacts with water in the vessel and produces sodium hydroxide (caustic soda) and hydrogen gas, while the mercury returns to the electrolytic cell to be used again.

   $$2\mathrm{Na}_{(Hg)} + 2\mathrm{H}_2\mathrm{O}_{(l)} \rightarrow 2\mathrm{NaOH}_{(aq)} + \mathrm{H}_{2(g)}$$

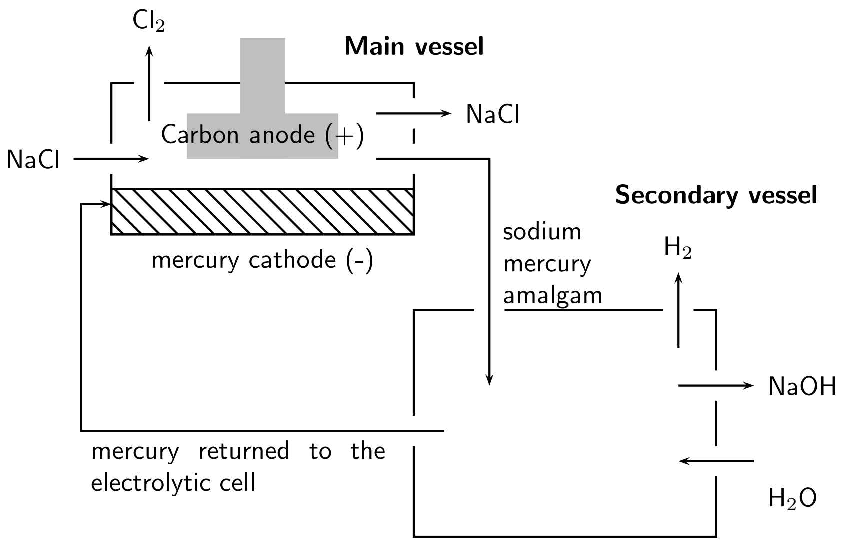


Figure 23.4: The Mercury Cell

This method, however, only produces a fraction of the chlorine and sodium hydroxide that is used by industry as it has certain disadvantages: mercury is expensive and toxic, and although it is returned to the electrolytic cell, some always escapes with the brine that has been used. The mercury reacts with the brine to form mercury(II) chloride. In the past this effluent was released into lakes and rivers, causing mercury to accumulate in fish and other animals feeding on the fish. Today, the brine is treated before it is discharged so that the environmental impact is lower.

2. **The Diaphragm Cell**

   In the diaphragm-cell (figure 23.5), a porous diaphragm divides the electrolytic cell, which contains brine, into an anode compartment and a cathode compartment. The brine is introduced into the anode compartment and flows through the diaphragm into the cathode compartment. When an electric current passes through the brine, the salt's chlorine ions and sodium ions move to the electrodes. Chlorine gas is produced at the anode. At the cathode, sodium ions react with water, forming caustic soda and hydrogen gas. Some salt remains in the solution with the caustic soda and can be removed at a later stage.

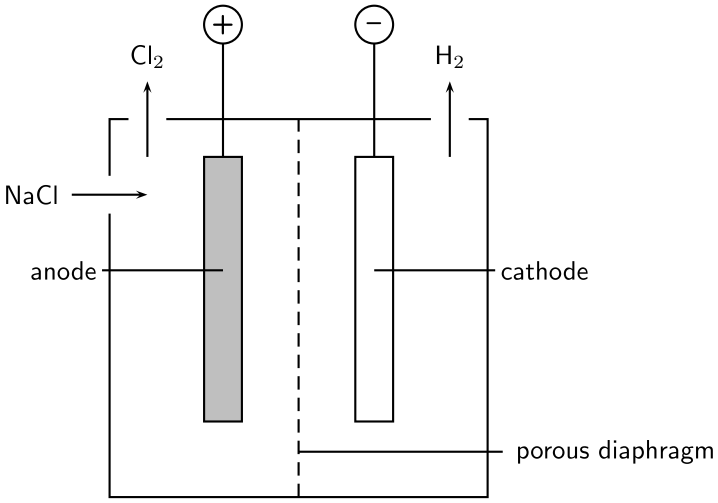


Figure 23.5: Diaphragm Cell

This method uses less energy than the mercury cell, but the sodium hydroxide is not as easily concentrated and precipitated into a useful substance.

To separate the chlorine from the sodium hydroxide, the two half-cells were traditionally separated by a porous asbestos diaphragm, which needed to be replaced every two months. This was damaging to the environment, as large quantities of asbestos had to be disposed. Today, the asbestos is being replaced by other polymers which do not need to be replaced as often.

3. **The Membrane Cell**

   The membrane cell (figure 23.6) is very similar to the diaphragm cell, and the same reactions occur. The main difference is that the two electrodes are separated by an ion-selective membrane, rather than by a diaphragm. The structure of the membrane is such that it allows cations to pass through it between compartments of the cell. It does not allow anions to pass through. This has nothing to do with the size of the pores, but rather with the charge on the ions. Brine is pumped into the anode compartment, and only the positively charged sodium ions pass into the cathode compartment, which contains pure water.

   At the positively charged anode, Cl^- ions from the brine are oxidised to Cl_2 gas.

$$2\mathrm{Cl}^- \rightarrow \mathrm{Cl}_{2(g)} + 2\mathrm{e}^-$$

   At the negatively charged cathode, hydrogen ions in the water are reduced to hydrogen gas.

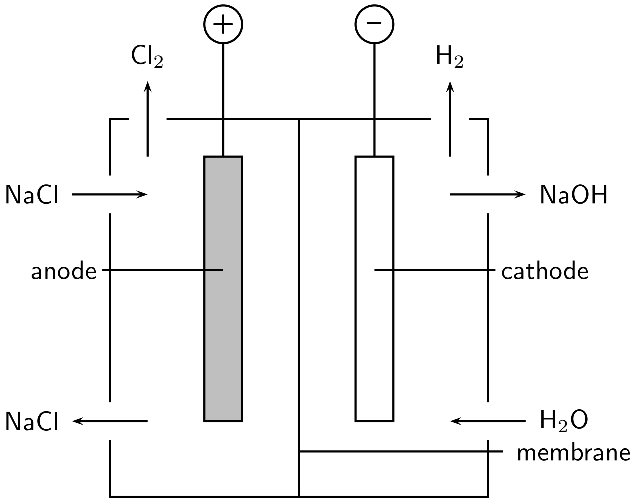


Figure 23.6: Membrane Cell

$$2H^+_{(aq)} + 2e^- \rightarrow H_{2(g)}$$

The Na^+ ions flow through the membrane to the cathode compartment and react with the remaining hydroxide (OH^-) ions from the water to form sodium hydroxide (NaOH). The chloride ions cannot pass through, so the chlorine does not come into contact with the sodium hydroxide in the cathode compartment. The sodium hydroxide is removed from the cell. The overall equation is as follows:

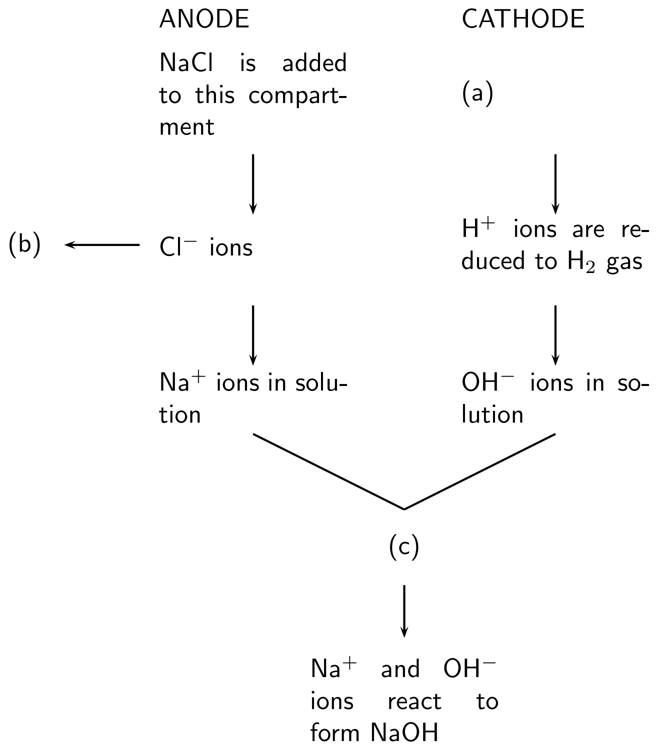
$$2NaCl + 2H_20 \rightarrow Cl_2 + H_2 + 2NaOH$$

The advantage of using this method is that the sodium hydroxide that is produced is very pure because it is kept separate from the sodium chloride solution. The caustic soda therefore has very little salt contamination. The process also uses less electricity and is cheaper to operate.

?

Exercise: The Chloralkali industry

1. Refer to the flow diagram below which shows the reactions that take place in the membrane cell, and then answer the questions that follow.



(a) What liquid is present in the cathode compartment at (a)?
(b) Identify the gas that is produced at (b).
(c) Explain one feature of this cell that allows the Na^+ and OH^- ions to react at (c).
(d) Give a balanced equation for the reaction that takes place at (c).

2. Summarise what you have learnt about the three types of cells in the chloralkali industry by completing the table below:

	Mercury cell	**Diaphragm cell**	**Membrane cell**
Main raw material			
Mechanism of separating Cl_2 and NaOH			
Anode reaction			
Cathode reaction			
Purity of NaOH produced			
Energy consumption			
Environmental impact			

23.3.2 Soaps and Detergents

Another important part of the chloralkali industry is the production of **soaps** and **detergents**. You will remember from an earlier chapter, that water has the property of *surface tension*. This means that it tends to bead up on surfaces and this slows down the wetting process and makes cleaning difficult. You can observe this property of surface tension when a drop of water falls onto a table surface. The drop holds its shape and does not spread. When cleaning, this surface tension must be reduced so that the water can spread. Chemicals that are able to do this are called **surfactants**. Surfactants also loosen, disperse and hold particles in suspension, all of which are an important part of the cleaning process. Soap is an example of one of these surfactants. Detergents contain one or more surfactants. We will go on to look at these in more detail.

Definition: Surfactant
A surfactant is a wetting agent that lowers the surface tension of a liquid, allowing it to spread more easily.

1. **Soaps**

   In chapter 10, a number of important biological macromolecules were discussed, including carbohydrates, proteins and nucleic acids. **Fats** are also biological macromolecules. A fat is made up of an alcohol called glycerol, attached to three fatty acids (figure 23.7). Each **fatty acid** is made up of a carboxylic acid attached to a long hydrocarbon chain. An **oil** has the same structure as a fat, but is a liquid rather than a solid. Oils are found in plants (e.g. olive oil, sunflower oil) and fats are found in animals.

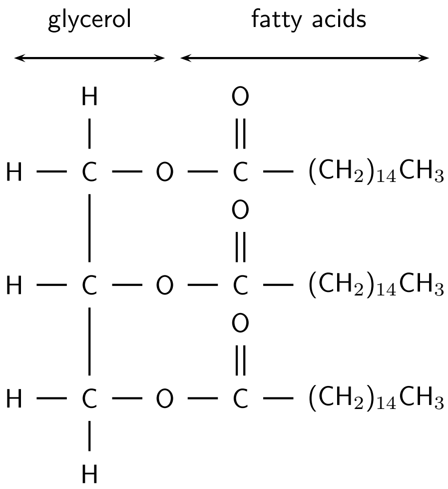


Figure 23.7: The structure of a fat, composed of an alcohol and three fatty acids

   To make soap, sodium hydroxide (NaOH) or potassium hydroxide (KOH) must be added to a fat or an oil. During this reaction, the glycerol is separated from the hydrocarbon chain in the fat, and is replaced by either potassium or sodium ions (figure 23.8). Soaps are the water-soluble sodium or potassium salts of fatty acids.

Soaps can be made from either fats or oils. Beef fat is a common source of fat, and vegetable oils such as palm oil are also commonly used.

   Fatty acids consist of two parts: a carboxylic acid group and a hydrocarbon chain. The hydrocarbon chain is *hydrophobic*, meaning that it is repelled by water. However, it is attracted to grease, oils and other dirt. The carboxylic acid is *hydrophilic*, meaning that it is attracted to water. Let's imagine that we have added soap to water in order to clean a dirty rugby jersey. The hydrocarbon chain will attach itself to the soil particles in the

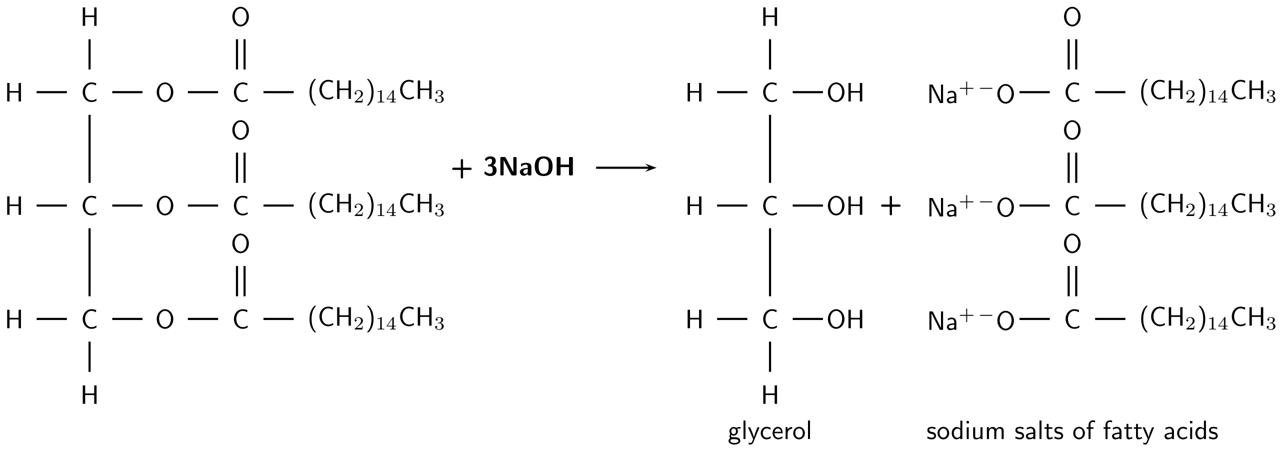


Figure 23.8: Sodium hydroxide reacts with a fat to produce glycerol and sodium salts of the fatty acids

jersey, while the carboxylic acid will be attracted to the water. In this way, the soil is pulled free of the jersey and is suspended in the water. In a washing machine or with vigourous handwashing, this suspension can be rinsed off with clean water.

Definition: Soap
Soap is a surfactant that is used with water for washing and cleaning. Soap is made by reacting a fat with either sodium hydroxide (NaOH) or potassium hydroxide (KOH).

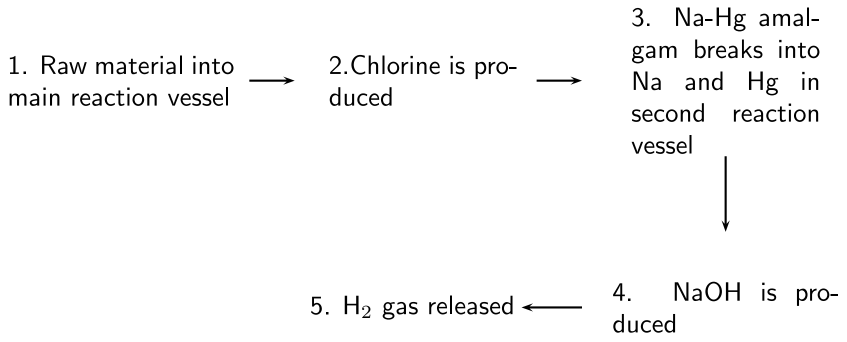
2. **Detergents**

Definition: Detergent
Detergents are compounds or mixtures of compounds that are used to assist cleaning. The term is often used to distinguish between soap and other chemical surfactants for cleaning.

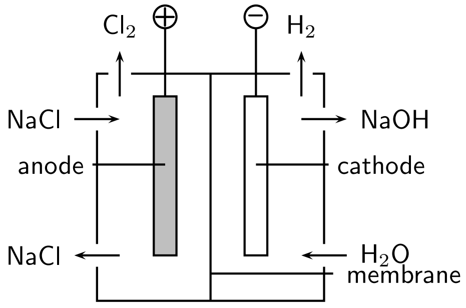
Detergents are also cleaning products, but are composed of one or more surfactants. Depending on the type of cleaning that is needed, detergents may contain one or more of the following:

- *Abrasives* to scour a surface.
- *Oxidants* for bleaching and disinfection.
- *Enzymes* to digest proteins, fats or carbohydrates in stains. These are called *biological detergents*.

Exercise: The choralkali industry



1. The diagram above shows the sequence of steps that take place in the mercury cell.
   (a) Name the 'raw material' in step 1.
   (b) Give the chemical equation for the reaction that produces chlorine in step 2.
   (c) What other product is formed in step 2.
   (d) Name the reactants in step 4.
2. Approximately 30 million tonnes of chlorine are used throughout the world annually. Chlorine is produced industrially by the electrolysis of brine. The diagram represents a membrane cell used in the production of Cl_2 gas.



   (a) What ions are present in the electrolyte in the left hand compartment of the cell?
   (b) Give the equation for the reaction that takes place at the anode.
   (c) Give the equation for the reaction that takes place at the cathode.
   (d) What ion passes through the membrane while these reactions are taking place?
   Chlorine is used to purify drinking water and swimming pool water. The substance responsible for this process is the weak acid, hypochlorous acid (HOCl).
   (e) One way of putting HOCl into a pool is to bubble chlorine gas through the water. Give an equation showing how bubbling $Cl_2(g)$ through water produces HOCl.
   (f) A common way of treating pool water is by adding 'granular chlorine'. Granular chlorine consists of the salt calcium hypochlorite, $Ca(OCl)_2$. Give an equation showing how this salt dissolves in water. Indicate the phase of each substance in the equation.
   (g) The OCl^- ion undergoes hydrolysis , as shown by the following equation:
   $$\mathrm{OCl^- + H_2O \Leftrightarrow HOCl + OH^-}$$
   Will the addition of granular chlorine to pure water make the water acidic, basic or will it remain neutral? Briefly explain your answer.

(IEB Paper 2, 2003)

23.4 The Fertiliser Industry

23.4.1 The value of nutrients

Nutrients are very important for life to exist. An **essential nutrient** is any chemical element that is needed for a plant to be able to grow from a seed and complete its life cycle. The same is true for animals. A *macronutrient* is one that is required in large quantities by the plant or animal, while a *micronutrient* is one that only needs to be present in small amounts for a plant or an animal to function properly.

Definition: Nutrient
A nutrient is a substance that is used in an organism's metabolism or physiology and which must be taken in from the environment.

In plants, the macronutrients include carbon (C), hydrogen (H), oxygen (O), nitrogen (N), phosphorus (P) and potassium (K). The source of each of these nutrients for plants, and their function, is summarised in table 23.1. Examples of micronutrients in plants include iron, chlorine, copper and zinc.

Table 23.1: The source and function of the macronutrients in plants

Nutrient	Source	Function
Carbon	Carbon dioxide in the air	Component of organic molecules such as carbohydrates, lipids and proteins
Hydrogen	Water from the soil	Component of organic molecules
Oxygen	Water from the soil	Component of organic molecules
Nitrogen	Nitrogen compounds in the soil	Part of plant proteins and chlorophyll. Also boosts plant growth.
Phosphorus	Phosphates in the soil	Needed for photosynthesis, blooming and root growth
Potassium	Soil	Building proteins, part of chlorophyll and reduces diseases in plants

Animals need similar nutrients in order to survive. However since animals can't photosynthesise, they rely on plants to supply them with the nutrients they need. Think for example of the human diet. We can't make our own food and so we either need to eat vegetables, fruits and seeds (all of which are direct plant products) or the meat of other animals which would have fed on plants during their life. So most of the nutrients that animals need are obtained either directly or indirectly from plants. Table 23.2 summarises the functions of some of the macronutrients in animals.

Micronutrients also play an important function in animals. Iron for example, is found in haemoglobin, the blood pigment that is responsible for transporting oxygen to all the cells in the body.

Nutrients then, are essential for the survival of life. Importantly, obtaining nutrients starts with plants, which are able either to photosynthesise or to absorb the required nutrients from the soil. It is important therefore that plants are always able to access the nutrients that they need so that they will grow and provide food for other forms of life.

23.4.2 The Role of fertilisers

Plants are only able to absorb soil nutrients in a particular form. Nitrogen for example, is absorbed as **nitrates**, while phosphorus is absorbed as **phosphates**. The **nitrogen cycle** (chapter

Table 23.2: The functions of animal macronutrients

Nutrient	Function
Carbon	Component of organic compounds
Hydrogen	Component of organic compounds
Oxygen	Component of organic compounds
Nitrogen	Component of nucleic acids and proteins
Phosphorus	Component of nucleic acids and phospholipids
Potassium	Helps in coordination and regulating the water balance in the body

19) describes the process that is involved in converting atmospheric nitrogen into a form that can be used by plants.

However, all these natural processes of maintaining soil nutrients take a long time. As populations grow and the demand for food increases, there is more and more strain on the land to produce food. Often, cultivation practices don't give the soil enough time to recover and to replace the nutrients that have been lost. Today, **fertilisers** play a very important role in restoring soil nutrients so that crop yields stay high. Some of these fertilisers are **organic** (e.g. compost, manure and fishmeal), which means that they started off as part of something living. Compost for example is often made up of things like vegetable peels and other organic remains that have been thrown away. Others are **inorganic** and can be made industrially. The advantage of these commercial fertilisers is that the nutrients are in a form that can be absorbed immediately by the plant.

Definition: Fertiliser

A fertiliser is a compound that is given to a plant to promote growth. Fertilisers usually provide the three major plant nutrients and most are applied via the soil so that the nutrients are absorbed by plants through their roots.

When you buy fertilisers from the shop, you will see three numbers on the back of the packet e.g. 18-24-6. These numbers are called the **NPK ratio**, and they give the percentage of nitrogen, phosphorus and potassium in that fertiliser. Depending on the types of plants you are growing, and the way in which you would like them to grow, you may need to use a fertiliser with a slightly different ratio. If you want to encourage root growth in your plant for example, you might choose a fertiliser with a greater amount of phosphorus. Look at the table below, which gives an idea of the amounts of nitrogen, phosphorus and potassium there are in different types of fertilisers. Fertilisers also provide other nutrients such as calcium, sulfur and magnesium.

Table 23.3: Common grades of some fertiliser materials

Description	Grade (NPK %)
Ammonium nitrate	34-0-0
Urea	46-0-0
Bone Meal	4-21-1
Seaweed	1-1-5
Starter fertilisers	18-24-6
Equal NPK fertilisers	12-12-12
High N, low P and medium K fertilisers	25-5-15

23.4.3 The Industrial Production of Fertilisers

The industrial production of fertilisers may involve several processes.

1. **Nitrogen fertilisers**

   Making **nitrogen fertilisers** involves producing *ammonia*, which is then reacted with *oxygen* to produce *nitric acid*. Nitric acid is used to acidify phosphate rock to produce nitrogen fertilisers. The flow diagram below illustrates the processes that are involved. Each of these steps will be examined in more detail.

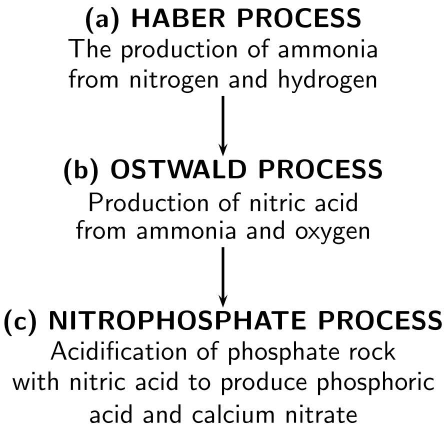


Figure 23.9: Flow diagram showing steps in the production of nitrogen fertilisers

(a) **The Haber Process**

The Haber process involves the reaction of nitrogen and hydrogen to produce ammonia. **Nitrogen** is produced through the **fractional distillation** of air. Fractional distillation is the separation of a mixture (remember that air is a mixture of different gases) into its component parts through various methods. **Hydrogen** can be produced through **steam reforming**. In this process, a hydrocarbon such as methane reacts with water to form carbon monoxide and hydrogen according to the following equation:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Nitrogen and hydrogen are then used in the Haber process. The equation for the Haber process is:

$$N_2(g) + 3H_2(g) \rightarrow 2NH_3(g)$$

(The reaction takes place in the presence of an iron (Fe) catalyst under conditions of 200 atmospheres (atm) and 450-500 degrees Celsius)

The Haber process developed in the early 20th century, before the start of World War 1. Before this, other sources of nitrogen for fertilisers had included saltpeter ($NaNO_3$) from Chile and guano. Guano is the droppings of seabirds, bats and seals. By the 20th century, a number of methods had been developed to 'fix' atmospheric nitrogen. One of these was the Haber process, and it advanced through the work of two German men, Fritz Haber and Karl Bosch (The process is sometimes also referred to as the 'Haber-Bosch process'). They worked out what the best conditions were in order to get a high yield of ammonia, and found these to be high temperature and high pressure. They also experimented with different catalysts to see which worked best in that reaction. During World War 1, the ammonia that was produced through the Haber process was used to make explosives. One of the advantages for Germany was that, having perfected the Haber process, they did not need to rely on other countries for the chemicals that they needed to make them.

(b) **The Ostwald Process**

The Ostwald process is used to produce nitric acid from ammonia. Nitric acid can then be used in reactions that produce fertilisers. Ammonia is converted to nitric acid in two stages. First, it is oxidised by heating with oxygen in the presence of a platinum catalyst to form nitric oxide and water. This step is strongly exothermic, making it a useful heat source.

$$4NH_3(g) + 5O_2(g) \rightarrow 4NO(g) + 6H_2O(g)$$

Stage two, which combines two reaction steps, is carried out in the presence of water. Initially nitric oxide is oxidised again to yield nitrogen dioxide:

$$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$$

This gas is then absorbed by the water to produce nitric acid. Nitric oxide is also a product of this reaction. The nitric oxide (NO) is recycled, and the acid is concentrated to the required strength.

$$3NO_2(g) + H_2O(l) \rightarrow 2HNO_3(aq) + NO(g)$$

(c) **The Nitrophosphate Process**

The nitrophosphate process involves acidifying phosphate rock with nitric acid to produce a mixture of phosphoric acid and calcium nitrate:

$$Ca_3(PO_4)_2 + 6HNO_3 + 12H_2O \rightarrow 2H_3PO_4 + 3Ca(NO_3)_2 + 12H_2O$$

When calcium nitrate and phosphoric acid react with ammonia, a compound fertiliser is produced.

$$Ca(NO_3)_2 + 4H_3PO_4 + 8NH_3 \rightarrow CaHPO_4 + 2NH_4NO_3 + 8(NH_4)2HPO_4$$

If potassium chloride or potassium sulphate is added, the result will be NPK fertiliser.

(d) **Other nitrogen fertilisers**

- Urea ($(NH_2)_2CO$) is a nitrogen-containing chemical product which is produced on a large scale worldwide. Urea has the highest nitrogen content of all solid nitrogeneous fertilisers in common use (46.4%) and is produced by reacting ammonia with carbon dioxide.

  Two reactions are involved in producing urea:

  i. $2NH_3 + CO_2 \rightarrow H_2N - COONH_4$
  ii. $H_2N - COONH_4 \rightarrow (NH_2)_2CO + H_2O$

- Other common fertilisers are ammonium nitrate and ammonium sulphate. Ammonium nitrate is formed by reacting ammonia with nitric acid.

  $$NH_3 + HNO_3 \rightarrow NH_4NO_3$$

  Ammonium sulphate is formed by reacting ammonia with sulphuric acid.

  $$2NH_3 + H_2SO_4 \rightarrow (NH_4)_2SO_4$$

2. **Phosphate fertilisers**

The production of phosphate fertilisers also involves a number of processes. The first is the production of sulfuric acid through the **contact process**. Sulfuric acid is then used in a reaction that produces phosphoric acid. Phosphoric acid can then be reacted with phosphate rock to produce triple superphosphates.

(a) *The production of sulfuric acid*

Sulfuric acid is produced from sulfur, oxygen and water through the contact process. In the first step, sulfur is burned to produce sulfur dioxide.

$$S(s) + O_2(g) \rightarrow SO_2(g)$$

This is then oxidised to sulfur trioxide using oxygen in the presence of a vanadium(V) oxide catalyst.

$$2SO_2 + O_2(g) \rightarrow 2SO_3(g)$$

Finally the sulfur trioxide is treated with water to produce 98-99% sulfuric acid.

$$SO_3(g) + H_2O(l) \rightarrow H_2SO_4(l)$$

(b) *The production of phosphoric acid*

The next step in the production of phosphate fertiliser is the reaction of sulfuric acid with phosphate rock to produce phosphoric acid (H_3PO_4). In this example, the phosphate rock is fluoropatite ($Ca_5F(PO_4)_3$).

$$Ca_5F(PO_4)_3 + 5H_2SO_4 + 10H_2O \rightarrow 5CaSO_42H_2O + HF + 3H_3PO_4$$

(c) *The production of phosphates and superphosphates*

When concentrated phosphoric acid reacts with ground phosphate rock, triple superphosphate is produced.

$$3Ca_3(PO_4)_2CaF_2 + 4H_3PO_4 + 9H_2O \rightarrow 9Ca(H_2PO_4)_2 + CaF_2$$

3. **Potassium**

   Potassium is obtained from **potash**, an impure form of potassium carbonate (K_2CO_3). Other potassium salts (e.g. KCl AND K_2O) are also sometimes included in fertilisers.

23.4.4 Fertilisers and the Environment: Eutrophication

Eutrophication is the enrichment of an ecosystem with chemical nutrients, normally by compounds that contain nitrogen or phosphorus. Eutrophication is considered a form of pollution because it promotes plant growth, favoring certain species over others. In aquatic environments, the rapid growth of certain types of plants can disrupt the normal functioning of an ecosystem, causing a variety of problems. Human society is impacted as well because eutrophication can decrease the resource value of rivers, lakes, and estuaries making recreational activities less enjoyable. Health-related problems can also occur if eutrophic conditions interfere with the treatment of drinking water.

Definition: Eutrophication
Eutrophication refers to an increase in chemical nutrients in an ecosystem. These chemical nutrients usually contain nitrogen or phosphorus.

In some cases, eutrophication can be a natural process that occurs very slowly over time. However, it can also be accelerated by certain human activities. Agricultural runoff, when excess fertilisers are washed off fields and into water, and sewage are two of the major causes of eutrophication. There are a number of impacts of eutrophication.

- *A decrease in biodiversity (the number of plant and animal species in an ecosystem)*

  When a system is enriched with nitrogen, plant growth is rapid. When the number of plants increases in an aquatic system, they can block light from reaching deeper. Plants also consume oxygen for respiration, and if the oxygen content of the water decreases too much, this can cause other organisms such as fish to die.

- *Toxicity*

  Sometimes, the plants that flourish during eutrophication can be toxic and may accumulate in the food chain.

South Africa's Department of Water Affairs and Forestry has a 'National Eutrophication Monitoring Programme' which was set up to monitor eutrophication in impoundments such as dams, where no monitoring was taking place.

Despite the impacts, there are a number of ways of preventing eutrophication from taking place. **Cleanup measures** can directly remove the excess nutrients such as nitrogen and phosphorus from the water. Creating **buffer zones** near farms, roads and rivers can also help. These act as filters and cause nutrients and sediments to be deposited there instead of in the aquatic system. **Laws** relating to the treatment and discharge of sewage can also help to control eutrophication. A final possible intervention is **nitrogen testing and modeling**. By assessing exactly how much fertiliser is needed by crops and other plants, farmers can make sure that they only apply just enough fertiliser. This means that there is no excess to run off into neighbouring streams during rain. There is also a cost benefit for the farmer.

Activity :: Discussion : Dealing with the consequences of eutrophication

In many cases, the damage from eutrophication is already done. In groups, do the following:

1. List all the possible consequences of eutrophication that you can think of.
2. Suggest ways to solve these problems, that arise because of eutrophication.

Exercise: Chemical industry: Fertilisers

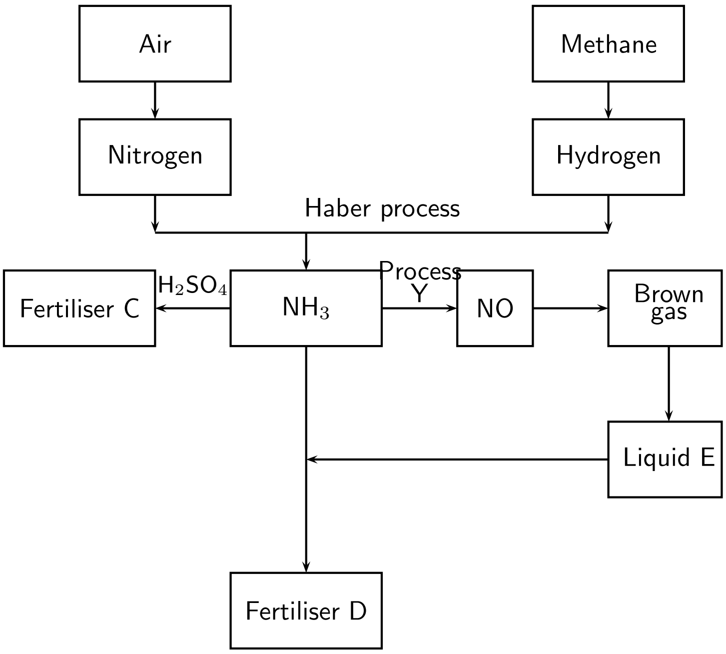
Why we need fertilisers

There is likely to be a gap between food production and demand in several parts of the world by 2020. Demand is influenced by population growth and urbanisation, as well as income levels and changes in dietary preferences.
The facts are as follows:

- There is an increasing world population to feed
- Most soils in the world used for large-scale, intensive production of crops lack the necessary nutrients for the crops

Conclusion: Fertilisers are needed!

The flow diagram below shows the main steps in the industrial preparation of two important solid fertilisers.



1. Write down the balanced chemical equation for the formation of the brown gas.
2. Write down the name of process Y.
3. Write down the chemical formula of liquid E.
4. Write down the chemical formulae of fertilisers C and D respectively.

   The following extract comes from an article on fertilisers:

   A world without food for its people
   A world with an environment poisoned through the actions of man
   Are two contributing factors towards a disaster scenario.

5. Write down THREE ways in which the use of fertilisers poisons the environment.

23.5 Electrochemistry and batteries

You will remember from chapter 17 that a **galvanic** cell (also known as a *voltaic* cell) is a type of electrochemical cell where a chemical reaction produces electrical energy. The **emf** of a galvanic cell is the difference in voltage between the two half cells that make it up. Galvanic cells have a number of applications, but one of the most important is their use in **batteries**. You will know from your own experience that we use batteries in a number of ways, including cars, torches, sound systems and cellphones to name just a few.

23.5.1 How batteries work

A battery is a device in which **chemical energy** is directly converted to **electrical energy**. It consists of one or more voltaic cells, each of which is made up of two half cells that are connected in series by a conductive electrolyte. The voltaic cells are connected in series in a battery. Each cell has a positive electrode (cathode), and a negative electrode (anode). These do not touch each other but are immersed in a solid or liquid electrolyte.

Each half cell has a net electromotive force (emf) or voltage. The voltage of the battery is the difference between the voltages of the half-cells. This potential difference between the two half cells is what causes an electric current to flow.

Batteries are usually divided into two broad classes:

- *Primary batteries* irreversibly transform chemical energy to electrical energy. Once the supply of reactants has been used up, the battery can't be used any more.
- *Secondary batteries* can be recharged, in other words, their chemical reactions can be reversed if electrical energy is supplied to the cell. Through this process, the cell returns to its original state. Secondary batteries can't be recharged forever because there is a gradual loss of the active materials and electrolyte. Internal corrosion can also take place.

23.5.2 Battery capacity and energy

The **capacity** of a battery, in other words its ability to produce an electric charge, depends on a number of factors. These include:

- **Chemical reactions**

  The chemical reactions that take place in each of a battery's half cells will affect the voltage across the cell, and therefore also its capacity. For example, nickel-cadmium (NiCd) cells measure about 1.2V, and alkaline and carbon-zinc cells both measure about 1.5 volts. However, in other cells such as Lithium cells, the changes in electrochemical potential are much higher because of the reactions of lithium compounds, and so lithium cells can produce as much as 3 volts or more. The concentration of the chemicals that are involved will also affect a battery's capacity. The higher the concentration of the chemicals, the greater the capacity of the battery.

- **Quantity of electrolyte and electrode material in cell**

  The greater the amount of electrolyte in the cell, the greater its capacity. In other words, even if the chemistry in two cells is the same, a larger cell will have a greater capacity than a small one. Also, the greater the surface area of the electrodes, the greater will be the capacity of the cell.

- **Discharge conditions**

  A unit called an **Ampere hour** (Ah) is used to describe how long a battery will last. An ampere hour (more commonly known as an **amp hour**) is the amount of electric charge that is transferred by a current of one ampere for one hour. Battery manufacturers use a standard method to rate their batteries. So, for example, a 100 Ah battery will provide a current of 5 A for a period of 20 hours at room temperature. The capacity of the battery will depend on the rate at which it is discharged or used. If a 100 Ah battery is discharged at 50 A (instead of 5 A), the capacity will be *lower* than expected and the battery will run out *before* the expected 2 hours.

  The relationship between the current, discharge time and capacity of a battery is expressed by **Peukert's law**:

  $$C_p = I^k t$$

  In the equation, 'C_p' represents the battery's capacity (Ah), I is the discharge current (A), k is the Peukert constant and t is the time of discharge (hours).

23.5.3 Lead-acid batteries

In a **lead-acid battery**, each cell consists of electrodes of lead (Pb) and lead (IV) oxide (PbO_2) in an electrolyte of sulfuric acid (H_2SO_4). When the battery discharges, both electrodes turn into lead (II) sulphate ($PbSO_4$) and the electrolyte loses sulfuric acid to become mostly water.

The chemical half reactions that take place at the anode and cathode when the battery is **discharging** are as follows:

Anode (oxidation): $\mathrm{Pb(s) + SO_4^{2-}(aq) \Leftrightarrow PbSO_4(s) + 2e^-}$ (E^0 = -0.356 V)

Cathode (reduction): $\mathrm{PbO_2(s) + SO_4^{2-}(aq) + 4H^+ + 2e^- \Leftrightarrow PbSO_4(s) + 2H_2O(l)}$ ($E^0 = 1.685$ V)

The overall reaction is as follows:

$$\mathrm{PbO_2(s) + 4H^+(aq) + 2SO_4^{2-}(aq) + Pb(s) \rightarrow 2PbSO_4(s) + 2H_2O(l)}$$

The emf of the cell is calculated as follows:

EMF = E (cathode)- E (anode)

EMF = +1.685 V - (-0.356 V)

EMF = +2.041 V

Since most batteries consist of six cells, the total voltage of the battery is approximately 12 V.

One of the important things about a lead-acid battery is that it can be **recharged**. The recharge reactions are the *reverse* of those when the battery is discharging.

The lead-acid battery is made up of a number of *plates* that maximise the surface area on which chemical reactions can take place. Each plate is a rectangular grid, with a series of holes in it. The holes are filled with a mixture of lead and sulfuric acid. This paste is pressed into the holes and the plates are then stacked together, with suitable separators between them. They are then placed in the battery container, after which acid is added (figure 23.10).

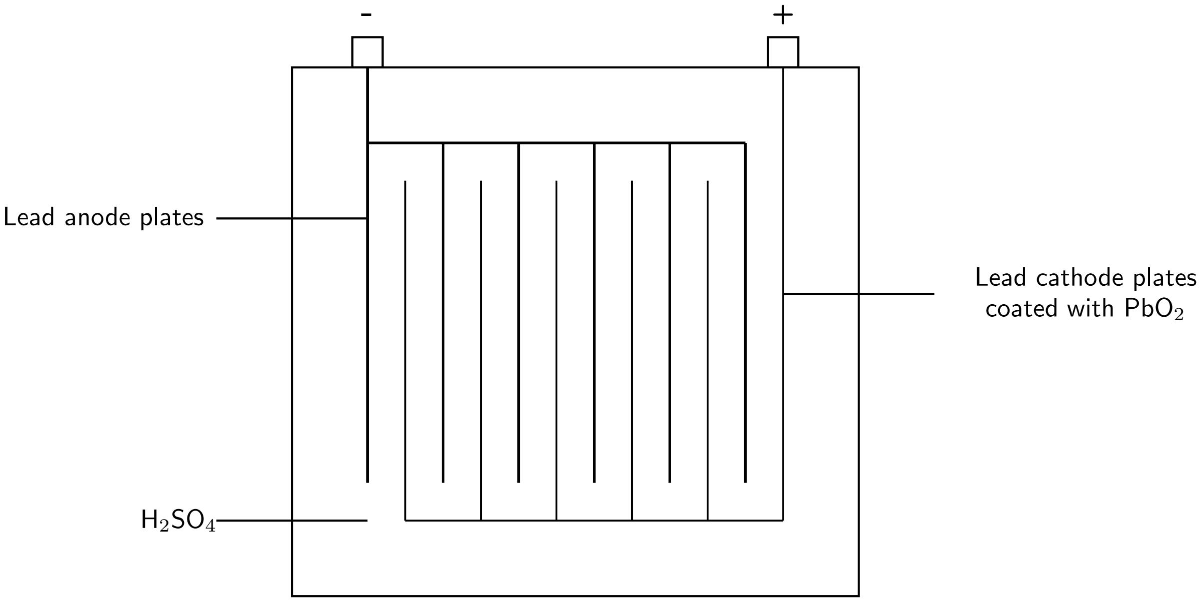


Figure 23.10: A lead-acid battery

Lead-acid batteries have a number of applications. They can supply high surge currents, are relatively cheap, have a long shelf life and can be recharged. They are ideal for use in cars, where they provide the high current that is needed by the starter motor. They are also used in forklifts and as standby power sources in telecommunication facilities, generating stations and computer data centres. One of the disadvantages of this type of battery is that the battery's lead must be recycled so that the environment doesn't become contaminated. Also, sometimes when the battery is charging, hydrogen gas is generated at the cathode and this can cause a small explosion if the gas comes into contact with a spark.

23.5.4 The zinc-carbon dry cell

A simplified diagram of a zinc-carbon cell is shown in figure 23.11.

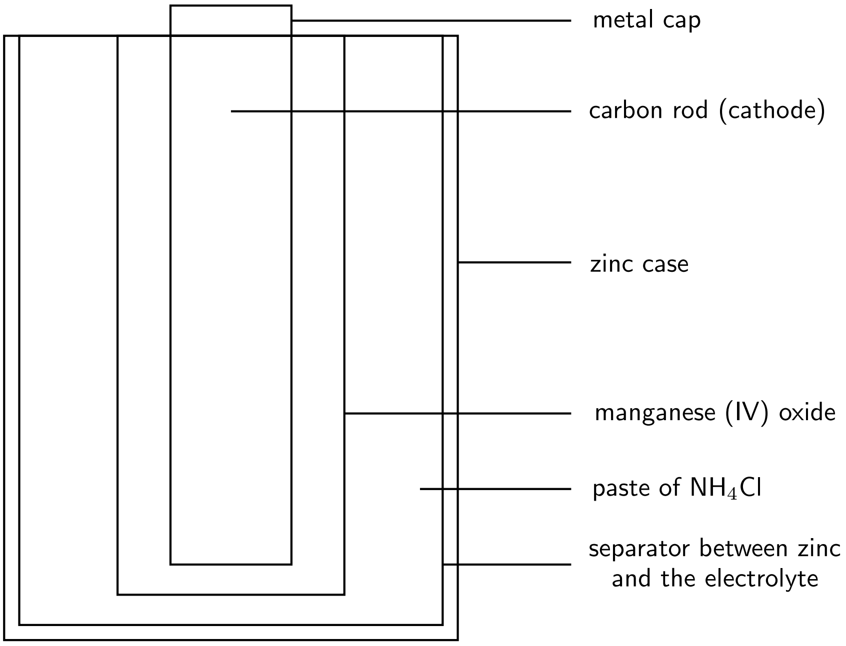


Figure 23.11: A zinc-carbon dry cell

A zinc-carbon cell is made up of an outer zinc container, which acts as the **anode**. The **cathode** is the central carbon rod, surrounded by a mixture of carbon and manganese (IV) oxide (MnO_2). The **electrolyte** is a paste of ammonium chloride (NH_4Cl). A fibrous fabric separates the two electrodes, and a brass pin in the centre of the cell conducts electricity to the outside circuit.

The paste of ammonium chloride reacts according to the following half-reaction:

$2NH_4^+(aq) + 2e^- \rightarrow 2NH_3(g) + H_2(g)$

The manganese(IV) oxide in the cell removes the hydrogen produced above, according to the following reaction:

$2MnO_2(s) + H_2(g) \rightarrow Mn_2O_3(s) + H_2O(l)$

The combined result of these two reactions can be represented by the following half reaction, which takes place at the cathode:

Cathode: $2NH_4^+(aq) + 2MnO_2(s) + 2e^- \rightarrow Mn_2O_3(s) + 2NH_3(g) + H_2O(l)$

The anode half reaction is as follows:

Anode: $\mathrm{Zn(s)} \rightarrow \mathrm{Zn^{2+}} + 2\mathrm{e^-}$

The overall equation for the cell is:

$$\mathrm{Zn(s)} + 2\mathrm{MnO_2(s)} + 2\mathrm{NH_4^+} \rightarrow \mathrm{Mn_2O_3(s)} + \mathrm{H_2O} + \mathrm{Zn(NH_3)_2^{2+}(aq)}\ (\mathrm{E^0} = 1.5\ \mathrm{V})$$

Alkaline batteries are almost the same as zinc-carbon batteries, except that the electrolyte is potassium hydroxide (KOH), rather than ammonium chloride. The two half reactions in an alkaline battery are as follows:

Anode: $\mathrm{Zn(s)} + 2\mathrm{OH^-(aq)} \rightarrow \mathrm{Zn(OH)_2(s)} + 2\mathrm{e^-}$

Cathode: $2\mathrm{MnO_2(s)} + \mathrm{H_2O(l)} + 2\mathrm{e^-} \rightarrow \mathrm{Mn_2O_3(s)} + 2\mathrm{OH^-(aq)}$

Zinc-carbon and alkaline batteries are cheap primary batteries and are therefore very useful in appliances such as remote controls, torches and radios where the power drain is not too high. The disadvantages are that these batteries can't be recycled and can leak. They also have a short shelf life. Alkaline batteries last longer than zinc-carbon batteries.

The idea behind today's common 'battery' was created by Georges Leclanche in France in the 1860's. The anode was a zinc and mercury alloyed rod, the cathode was a porous cup containing crushed $\mathrm{MnO_2}$. A carbon rod was inserted into this cup. The electrolyte was a liquid solution of ammonium chloride, and the cell was therefore called a *wet cell*. This was replaced by the *dry cell* in the 1880's. In the dry cell, the zinc can which contains the electrolyte, has become the anode, and the electrolyte is a paste rather than a liquid.

23.5.5 Environmental considerations

While batteries are very convenient to use, they can cause a lot of damage to the environment. They use lots of valuable resources as well as some potentially hazardous chemicals such as lead, mercury and cadmium. Attempts are now being made to recycle the different parts of batteries so that they are not disposed of in the environment, where they could get into water supplies, rivers and other ecosystems.

Exercise: Electrochemistry and batteries

A dry cell, as shown in the diagram below, does not contain a liquid electrolyte. The electrolyte in a typical zinc-carbon cell is a moist paste of ammonium chloride and zinc chloride.

(NOTE TO SELF: Insert diagram)

The paste of ammonium chloride reacts according to the following half-reaction:

$$2\mathrm{NH_4^+(aq)} + 2\mathrm{e^-} \rightarrow 2\mathrm{NH_3(g)} + \mathrm{H_2(g)}\ \text{(a)}$$

Manganese(IV) oxide is included in the cell to remove the hydrogen produced during half-reaction (a), according to the following reaction:

$$2\mathrm{MnO_22(s)} + \mathrm{H_2(g)} \rightarrow \mathrm{Mn_2O_3(s)} + \mathrm{H_2O(l)}\ \text{(b)}$$

The combined result of these two half-reactions can be represented by the following half reaction:

$$2NH_4^+(aq) + 2MnO_2(s) + 2e^- \rightarrow Mn_2O_3(s) + 2NH_3(g) + H_2O(l) \text{ (c)}$$

1. Explain why it is important that the hydrogen produced in half-reaction (a) is removed by the manganese(IV) oxide.
   In a zinc-carbon cell, such as the one above, half-reaction (c) and the half-reaction that takes place in the Zn/Zn^{2+} half-cell, produce an emf of 1,5 V under standard conditions.
2. Write down the half-reaction occurring at the anode.
3. Write down the net ionic equation occurring in the zinc-carbon cell.
4. Calculate the reduction potential for the cathode half-reaction.
5. When in use the zinc casing of the dry cell becomes thinner, because it is oxidised. When not in use, it still corrodes. Give a reason for the latter observation.
6. Dry cells are generally discarded when 'flat'. Why is the carbon rod the most useful part of the cell, even when the cell is flat?

(DoE Exemplar Paper 2, 2007)

23.6 Summary

- The growth of South Africa's **chemical industry** was largely because of the mines, which needed explosives for their operations. One of South Africa's major chemical companies is **Sasol**. Other important chemical industries in the country are the **chloralkali** and **fertiliser** industries.
- All countries need energy resources such as oil and natural gas. Since South Africa doesn't have either of these resources, Sasol technology has developed to convert **coal** into liquid fuels.
- Sasol has three main operation focus areas: Firstly, the conversion of **coal to liquid fuel**, secondly the production and **refinement of crude oil** which has been imported, and thirdly the production of **liquid fuels from natural gas**.
- The conversion of coal to liquid fuels involves a **Sasol/Lurgi gasification** process, followed by the conversion of this synthesis gas into a range of hydrocarbons, using the **Fischer-Tropsch technology** in **SAS reactors**.
- Heavy hydrocarbons can be converted into light hydrcarbons through a process called **cracking**. Common forms of cracking are **hydrocracking** and **steam cracking**.
- With regard to crude oil, Sasol imports crude oil from Gabon and then refines this at the **Natref refinery**.
- Gas from Mozambique can be used to produce liquid fuels, through two processes: First, the gas must pass through an autothermal reactor to produce a synthesis gas. Secondly, this synthesis gas is passed through a **Sasol Slurry Phase Distillate** process to convert the gas to hydrocarbons.
- All industries have an impact on the **environment** through the consumption of natural resources such as water, and through the production of pollution gases such as carbon dioxide, hydrogen sulfides, nitrogen oxides and others.
- The **chloralkali industry** produces **chlorine** and **sodium hydroxide**. The main raw material is **brine** (NaCl).

- In industry, **electrolytic cells** are used to split the sodium chloride into its component ions to produce chlorine and sodium hydroxide. One of the challenges in this process is to keep the products of the electrolytic reaction (i.e. the chlorine and the sodium hydroxide) separate so that they don't react with each other. Specially designed electrolytic cells are needed to do this.
- There are three types of electrolytic cells that are used in this process: **mercury cell**, the **diaphragm cell** and the **membrane cell**.
- The **mercury cell** consists of two reaction vessels. The first reaction vessel contains a mercury cathode and a carbon anode. An electric current passed through the brine produces Cl^- and Na^+ ions. The Cl^- ions are oxidised to form chlorine gas at the anode. Na^+ ions combine with the mercury cathode to form a sodium-mercury amalgam. The sodium-mercury amalgam passes into the second reaction vessel containing water, where the Na^+ ions react with hydroxide ions from the water. Sodium hydroxide is the product of this reaction.
- One of the **environmental impacts** of using this type of cell, is the use of **mercury**, which is highly toxic.
- In the **diaphragm cell**, a porous diaphragm separates the anode and the cathode compartments. Chloride ions are oxidised to chlorine gas at the anode, while sodium ions produced at the cathode react with water to produce sodium hydroxide.
- The **membrane cell** is very similar to the diaphragm cell, except that the anode and cathode compartments are separated by an **ion-selective membrane** rather than by a diaphragm. Brine is only pumped into the anode compartment. Positive sodium ions pass through the membrane into the cathode compartment, which contains water. As with the other two cells, chlorine gas is produced at the anode and sodium hydroxide at the cathode.
- One use of sodium hydroxide is in the production of **soaps and detergents**, and so this is another important part of the chloralkali industry.
- To make soap, sodium hydroxide or potassium hydroxide react with a fat or an oil. In the reaction, the sodium or potassium ions replace the alcohol in the fat or oil. The product, a **sodium or potassium salt of a fatty acid**, is what soap is made of.
- The fatty acids in soap have a **hydrophilic** and a **hydrophobic** part in each molecule, and this helps to loosen dirt and clean items.
- **Detergents** are also cleaning products, but are made up of a mixture of compounds. They may also have other components added to them to give certain characteristics. Some of these additives may be abrasives, oxidants or enzymes.
- The **fertiliser industry** is another important chemical industry.
- All plants need certain **macronutrients** (e.g. carbon, hydrogen, oxygen, potassium, nitrogen and phosphorus) and **micronutrients** (e.g. iron, chlorine, copper and zinc) in order to survive. Fertilisers provide these nutrients.
- In plants, most nutrients are obtained from the atmosphere or from the soil.
- Animals also need similar nutrients, but they obtain most of these directly from plants or plant products. They may also obtain them from other animals, whcih may have fed on plants during their life.
- The fertiliser industry is very important in ensuring that plants and crops receive the correct nutrients in the correct quantities to ensure maximum growth.
- **Nitrogen fertilisers** can be produced industrially using a number of chemical processes: The **Haber process** reacts nitrogen and hydrogen to produce **ammonia**; the **Ostwald process** reacts oxygen and ammonia to produce **nitric acid**; the **nitrophosphate process** reacts nitric acid with phosphate rock to produce compound fertilisers.

- **Phosphate fertilisers** are also produced through a series of reactions. The **contact process** produces **sulfuric acid**. Sulfuric acid then reacts with phosphate rock to produce **phosphoric acid**, after which phosphoric acid reacts with ground phosphate rock to produce fertilisers such as **triple superphosphate**.
- Potassium is obtained from **potash**.
- Fertilisers can have a damaging effect on the environment when they are present in high quantities in ecosystems. They can lead to **eutrophication**. A number of preventative actions can be taken to reduce these impacts.
- Another important part of the chemical industry is the production of **batteries**.
- A battery is a device that changes chemical energy into electrical energy.
- A battery consists of one or more **voltaic cells**, each of which is made up of two half cells that are connected in series by a conductive electrolyte. Each half cell has a net electromotive force (emf) or voltage. The net voltage of the battery is the difference between the voltages of the half-cells. This potential difference between the two half cells is what causes an electric current to flow.
- A **primary battery** cannot be recharged, but a **secondary battery** can be recharged.
- The **capacity** of a battery depends on the **chemical reactions** in the cells, the **quantity of electrolyte and electrode material** in the cell, and the **discharge conditions** of the battery.
- The relationship between the current, discharge time and capacity of a battery is expressed by **Peukert's law**:

  $$C_p = I^k t$$

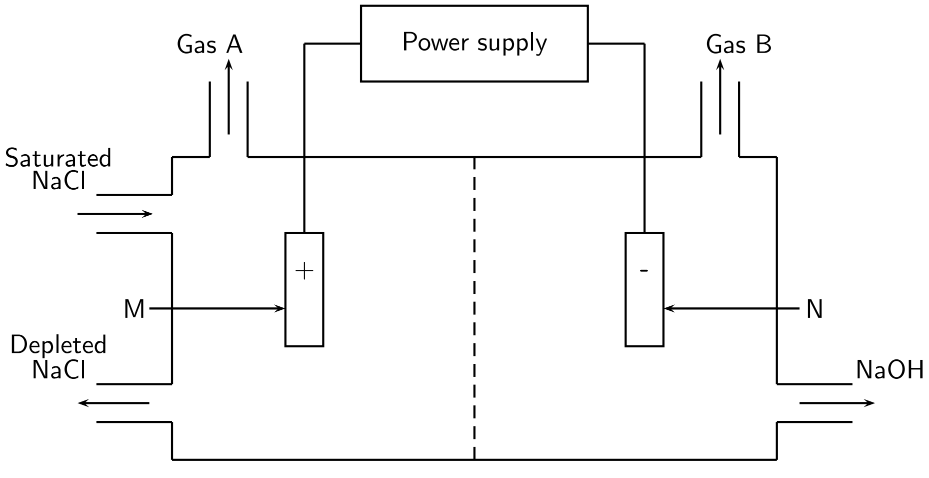
  In the equation, 'C_p' represents the battery's capacity (Ah), I is the discharge current (A), k is the Peukert constant and t is the time of discharge (hours).
- Two common types of batteries are **lead-acid batteries** and the **zinc-carbon dry cell**.
- In a **lead-acid battery**, each cell consists of electrodes of lead (Pb) and lead (IV) oxide (PbO_2) in an electrolyte of sulfuric acid (H_2SO_4). When the battery discharges, both electrodes turn into lead (II) sulphate ($PbSO_4$) and the electrolyte loses sulfuric acid to become mostly water.
- A **zinc-carbon cell** is made up of an outer zinc container, which acts as the **anode**. The cathode is the central carbon rod, surrounded by a mixture of carbon and manganese (IV) oxide (MnO_2). The electrolyte is a paste of ammonium chloride (NH_4Cl). A fibrous fabric separates the two electrodes, and a brass pin in the centre of the cell conducts electricity to the outside circuit.
- Despite their many advantages, batteries are made of potentially toxic materials and can be damaging to the **environment**.

Exercise: Summary Exercise

1. Give one word or term for each of the following descriptions:
   (a) A solid organic compound that can be used to produce liquid fuels.
   (b) The process used to convert heavy hydrocarbons into light hydrocarbons.
   (c) The process of separating nitrogen from liquid air.
   (d) The main raw material in the chloralkali industry.
   (e) A compound given to a plant to promote growth.

   (f) An electrolyte used in lead-acid batteries.

2. Indicate whether each of the following statements is true or false. If the statement is false, rewrite the statement correctly.
   (a) The longer the hydrocarbon chain in an organic compound, the more likely it is to be a solid at room temperature.
   (b) The main elements used in fertilisers are nitrogen, phosphorus and potassium.
   (c) A soap molecule is composed of an alcohol molecule and three fatty acids.
   (d) During the industrial preparation of chlorine and sodium hydroxide, chemical energy is converted to electrical energy.
3. For each of the following questions, choose the one correct answer from the list provided.
   (a) The sequence of processes that best describes the conversion of coal to liquid fuel is:
      i. coal → gas purification → SAS reactor → liquid hydrocarbon
      ii. coal → autothermal reactor → Sasol slurry phase F-T reactor → liquid hydrocarbon
      iii. coal → coal purification → synthesis gas → oil
      iv. coal → coal gasification → gas purification → SAS reactor → liquid hydrocarbons
   (b) The half-reaction that takes place at the cathode of a mercury cell in the chloralkali industry is:
      i. $2Cl^- \rightarrow Cl_2 + 2e^-$
      ii. $2Na^+ + 2e^- \rightarrow 2Na$
      iii. $2H^+ + 2e^- \rightarrow H_2$
      iv. $NaCl + H_2O \rightarrow NaOH + HCl$
   (c) In a zinc-carbon dry cell...
      i. the electrolyte is manganese (IV) oxide
      ii. zinc is oxidised to produce electrons
      iii. zinc is reduced to produce electrons
      iv. manganese (IV) dioxide acts as a reducing agent
4. **Chloralkali manufacturing process**
   The chloralkali (also called 'chlorine-caustic') industry is one of the largest electrochemical technologies in the world. Chlorine is produced using three types of electrolytic cells. The simplified diagram below shows a membrane cell.

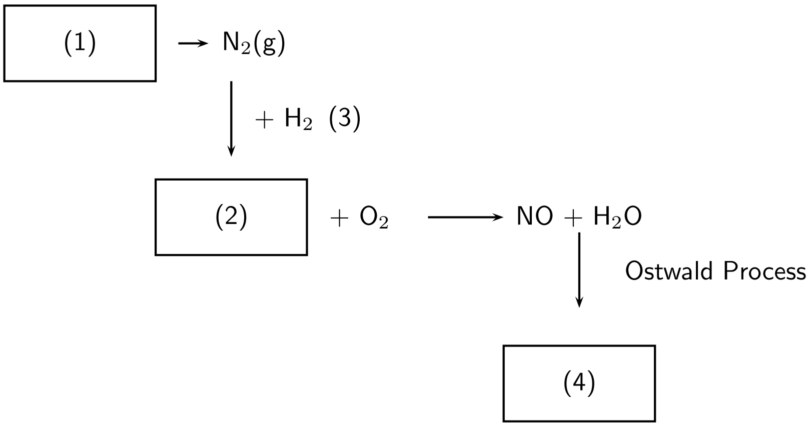


   (a) Give two reasons why the membrane cell is the preferred cell for the preparation of chlorine.
   (b) Why do you think it is advisable to use inert electrodes in this process?
   (c) Write down the equation for the half-reaction taking place at electrode M.
   (d) Which gas is chlorine gas? Write down only Gas A or Gas B.

(e) Briefly explain how sodium hydroxide forms in this cell.

(DoE Exemplar Paper 2,2007)

5. The production of nitric acid is very important in the manufacture of fertilisers. Look at the diagram below, which shows part of the fertiliser production process, and then answer the questions that follow.



(a) Name the process at (1).
(b) Name the gas at (2).
(c) Name the process at (3) that produces gas (2).
(d) Name the product at (4).
(e) Name two fertilisers that can be produced from nitric acid.

6. A lead-acid battery has a number of different components. Match the description in Column A with the correct word or phrase in Column B. All the descriptions in Column A relate to lead-acid batteries.

Column A	Column B
The electrode metal	Lead sulphate
Electrolyte	Mercury
A product of the overall cell reaction	Electrolytic
An oxidising agent in the cathode half-reaction	Lead
Type of cells in a lead-acid battery	Sulfuric acid
	Ammonium chloride
	Lead oxide
	Galvanic

Appendix A

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