Atmosphere

Learning Outcomes:

(A) Air

- describe the volume composition of gases present in dry air as being approximately 78% nitrogen, 21% oxygen and the remainder being noble gases (with argon as the main constituent) and carbon dioxide

(B) Air Pollution

- name some common atmospheric pollutants, e.g. carbon monoxide; methane; nitrogen oxides (NO and NO_2); ozone; sulfur dioxide; unburnt hydrocarbons
- state the sources of these pollutants as (i) carbon monoxide from incomplete combustion of carbon-containing substances; (ii) nitrogen oxides from lightning activity and internal combustion engines; (iii) sulfur dioxide from volcanoes and combustion of fossil fuels
- discuss some of the effects of these pollutants on health and on the environment, e.g. the toxic nature of carbon monoxide, the role of nitrogen dioxide and sulfur dioxide in the formation of 'acid rain' and its effects on respiration and buildings

(C) Reducing Air Pollution

- describe the reactions used in possible solutions to the problems arising from common atmospheric pollutants, e.g. the redox reactions in catalytic converters to remove combustion pollutants, the use of calcium carbonate to reduce the effect of 'acid rain' and in flue gas desulfurisation

(D) Global Warming and the Carbon Cycle

- describe the carbon cycle in simple terms, to include (i) the processes of combustion, respiration and photosynthesis; (ii) how the carbon cycle regulates the amount of carbon dioxide in the atmosphere
- state that carbon dioxide and methane are greenhouse gases and may contribute to global warming, give the sources of these gases and discuss the possible consequences of an increase in global warming

(E) Depletion of Ozone Layer

- discuss the importance of the ozone layer and the problems involved with the depletion of ozone by reaction with chlorine containing compounds, chlorofluorocarbons (CFCs)

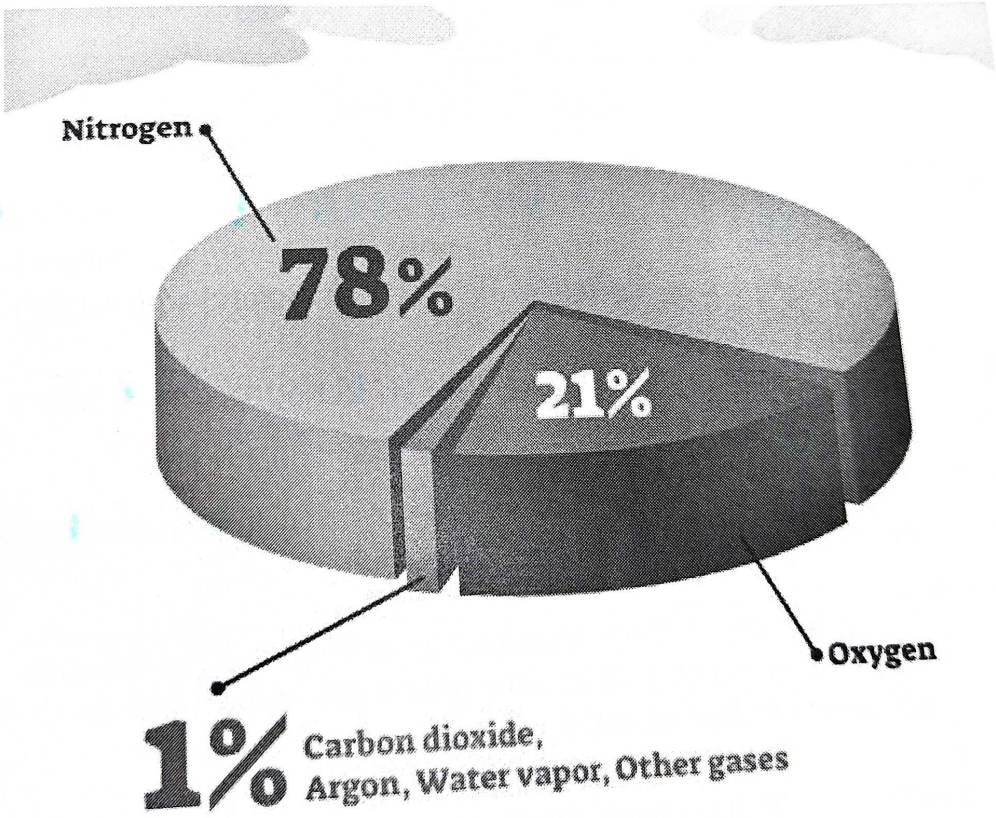
(A) AIR

1. Composition of Air

Air is a mixture consisting of elements and compounds. The table below shows the composition by volume of clean, dry air.

Gases	Composition by volume
Nitrogen , N_2	78 %
Oxygen, O_2	21 %
Noble gases (mainly argon, Ar)	1 % (Argon - 0.93%)
Carbon dioxide, CO_2	0.03 %

Note: The composition of air varies with time and place. (e.g. the amount of water vapour in air can vary from almost 0% in a desert to about 5% in a tropical forest)

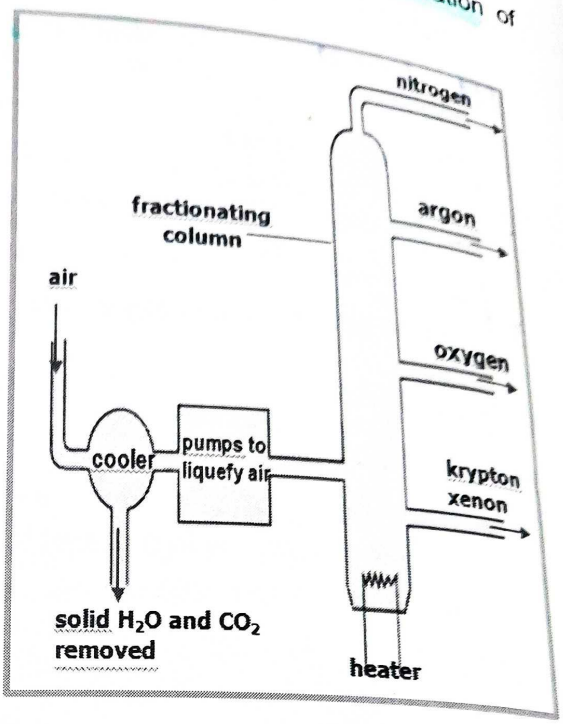


2. Fractional Distillation of Liquid Air

The components in air can be easily separated by physical means, fractional distillation of liquefied air.

This process is shown below:

Gas	Boiling point / °C
water vapour	100
carbon dioxide	-78 (sublimes)
xenon	-108
krypton	-153
oxygen	-183
argon	-186
nitrogen	-196



Step 1	Air is first cooled to freeze **water vapour** and **carbon dioxide.** These two compounds are removed to prevent them from blocking the pipes when they solidify during the cooling and liquefaction of air.
Step 2	The remaining gases in air are then **compressed** to about 150 atm in a compressor with huge pumps.
Step 3	When the compressed air is then allowed to **expand** rapidly, it cools, hence liquefying the air.
Step 4	The liquid air is then **distilled** in a fractionating column. An electric heater is used to boil it. The gases are separated according to their difference in boiling points. Nitrogen has the lowest boiling point and it boils first and is collected at the **top** of the column. The other gases come out at the column at different **heights** of the column depending on their boiling points. Krypton and xenon (other noble gases) must be further distilled to separate them.

(B) AIR POLLUTION

1. What is Air Pollution?

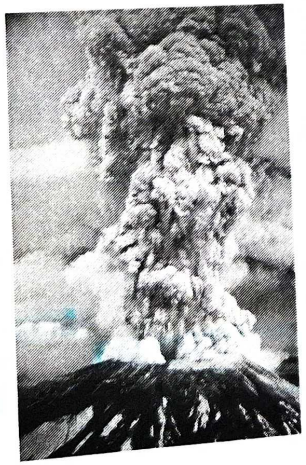
- Air pollution is a condition in which air contains a **high concentration** of **chemicals** that may **harm living things** or **damage non-living things.**
- Air pollution is caused by **pollutants** such as **solid particles** (particulates, e.g. soot) and **harmful gases** (carbon monoxide, sulfur dioxide, etc.) released into the Earth's atmosphere.

2. Types of air pollutants

Air Pollutants	Major Sources	Harmful Effects
(a) ***Carbon monoxide*** - a **colourless** & **odourless** gas (hence giving no warning of its presence)	**Incomplete combustion*** **of carbon-containing fuels** e.g. petrol and diesel in combustion engines of motor vehicles. **refer to page E9 for more information on incomplete combustion.*	Normally, oxygen combines with haemoglobin in red blood cells to form oxyhaemoglobin. **oxygen + haemoglobin ⇌ oxyhaemoglobin** The oxyhaemoglobin then moves through our bodies, releasing the oxygen to where it's needed. This process is **reversible**. **In the presence of CO:** Carbon monoxide binds with **haemoglobin** in the blood more readily compared to **oxygen** gas. **carbon monoxide + haemoglobin → carboxyhaemoglobin** This process is **irreversible**. **Health effect** • Carbon monoxide prevents uptake of **oxygen** gas by the **organs**. Hence, carbon monoxide gas is a **highly toxic gas** as it can then lead to **brain damage** and **death**.

Treatment or Prevention of Carbon Monoxide

- Carbon monoxide pollution can be reduced by fitting motor vehicles with **catalytic converters**.
- The catalytic converter **oxidises** the harmful carbon monoxide into **harmless carbon dioxide**.

Air Pollutants	Major Sources	Harmful Effects
(b) **Sulfur dioxide** - a **colourless** and **pungent** gas	• Combustion of **fossil fuels** such as **coal** and **petroleum (crude oil)** that contain sulfur as **impurities**. E.g. burning of coal in power stations. • **Volcanic** eruptions **(Natural source)** 	**Health effect** • causes **eye** irritations and **breathing difficulties** • high levels will lead to inflammation of the lungs (bronchitis) **Environmental effect** • gives rise to **acid** rain, with pH of about **4** and below Note: **Unpolluted rain water** has a pH of 6.5 because carbon dioxide in air dissolves in rain water to form carbonic acid. Equation: $CO_2(g) + H_2O(l) \rightleftharpoons H_2CO_3(aq)$ **Formation of acid rain** Step1: Sulfur (in coal / petroleum) burns in **air (oxygen)** to form sulfur dioxide. Equation: $\mathbf{S(s) + O_2(g) \rightarrow SO_2(g)}$ Step 2: Sulfur dioxide in the air reacts with water to form **sulfurous** acid, which is slowly **oxidised** in air to form **sulfuric acid**. Equations: $\mathbf{SO_2(g) + H_2O(l) \rightarrow H_2SO_3(aq)}$ $\mathbf{2H_2SO_3(aq) + O_2(g) \rightarrow 2H_2SO_4(aq)}$ **Harmful effect of acid rain** 1) Corrodes **limestone buildings** and **marble statues** by reacting with carbonates. 2) Corrodes **metal** structures such as steel bridges. 3) Damages **trees** and **vegetation**. Nutrients such as K^+ and Ca^{2+} from the soil needed by trees for good growth are dissolved by acidic rain and washed away. 4) Destroys **aquatic** life by killing **fish** in freshwater lakes and streams.

Prevention / Treatment

1. **Remove sulfur impurities from fossil fuels** before they are burnt. However, this method is expensive and technologically difficult to accomplish.

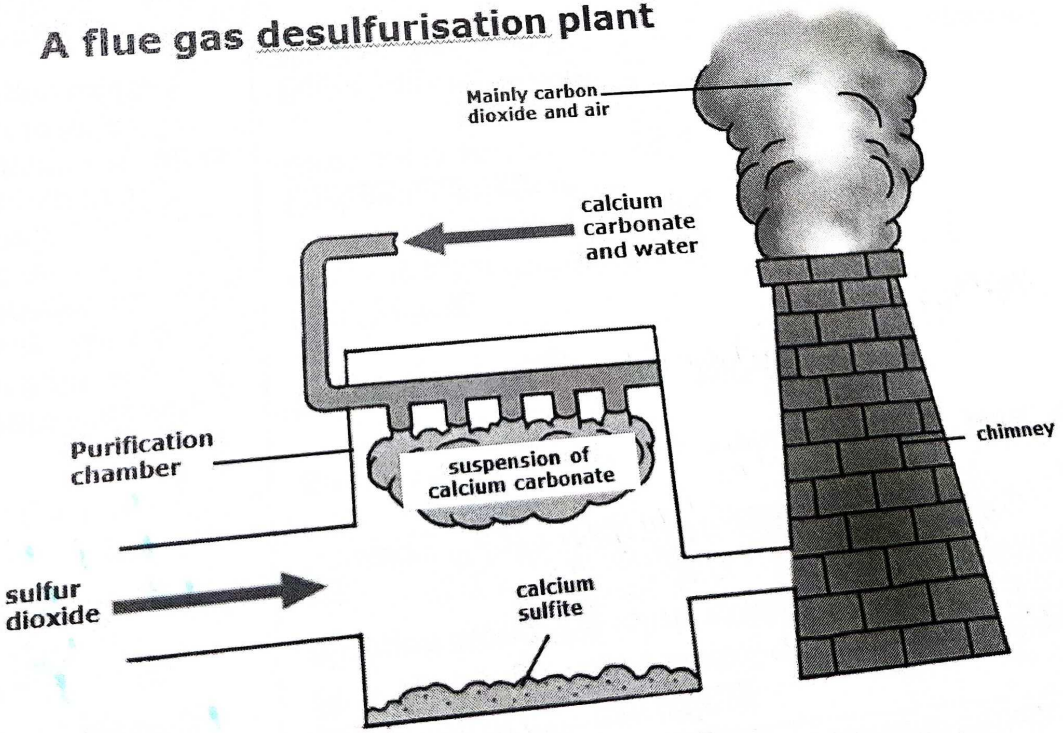
2. **Flue Gas Desulfurisation**
   Treat acidic sulfur dioxide gas from the waste gases formed before they are released into the air.
   - The waste gases known as **flue gases** are treated with a **wet** mixture of **calcium carbonate**.
   - The acidic sulfur dioxide is removed in the following reaction:

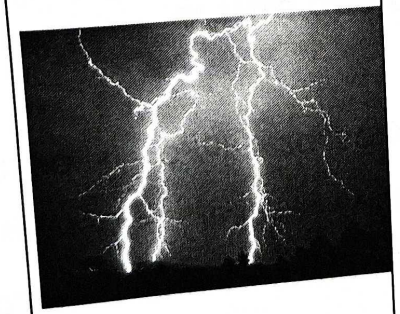
   Equation: $SO_2(g) + CaCO_3(s) \rightarrow CaSO_3(s) + CO_2(g)$

   - The calcium sulfite, $CaSO_3$, is further **oxidised** to **calcium sulfate, $CaSO_4$.**

   Equation: $2CaSO_3(s) + O_2(g) \rightarrow 2CaSO_4(s)$

A flue gas desulfurisation plant



Air Pollutants	Major Sources	Harmful Effects
(c) ***Oxides of Nitrogen*** E.g.: **NO, nitrogen monoxide / nitric oxide** (colourless & pungent gas) and **NO_2, nitrogen dioxide** (brown & pungent gas) These two oxides of nitrogen are often described simply as **NO_x**.	• Internal combustion engines **of motor vehicles** when **nitrogen** and **oxygen** from **air react** at **high temperature.** • **Occurs naturally** from **lightning** activity. During thunderstorms, the **heat** released by **lightning** causes **nitrogen** and **oxygen** in the **air** to react to form nitrogen oxides. 	**Formation of nitrogen oxides** Step 1: At **high** temperature, **nitrogen** gas and **oxygen** gas from **air** react to form **nitrogen monoxide (nitric oxide).** Equation: $N_2(g) + O_2(g) \rightarrow 2NO(g)$ Step 2: The nitrogen monoxide reacts with more oxygen to become **nitrogen dioxide**. Equation: $2NO(g) + O_2(g) \rightarrow 2NO_2(g)$ **Health effect** Similar to sulfur dioxide **Environmental effect** Gives rise to **acid** rain **Formation of acid rain** Nitrogen dioxide reacts with oxygen and the water vapour in the air to form **nitric** acid. Equation: $4NO_2(g) + O_2(g) + 2H_2O(l) \rightarrow 4HNO_3(aq)$ **Harmful effect of acid rain** Similar to sulfur dioxide

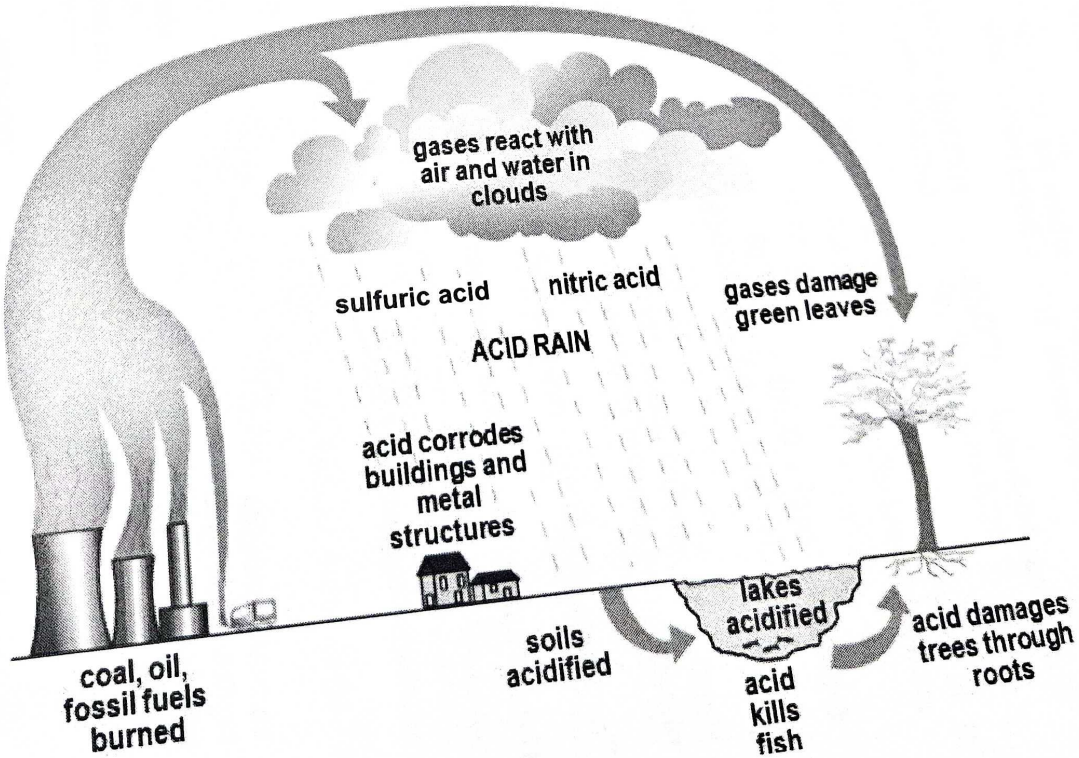
Treatment and Prevention of Nitrogen oxides
The production of **NO_x** can be greatly reduced by fitting motor vehicles with **catalytic converters**. In the converter, the oxides of nitrogen are **reduced** to harmless **nitrogen** gas.

Formation of acid rain

- Sulfur dioxide (SO_2) and nitrogen dioxide (NO_2) are <u>acidic oxides</u> that react with oxygen and water vapour in the air to form sulfuric acid and nitric acid which become acid rain.

sulfur dioxide	+ oxygen + water vapour	→	**sulfuric acid**
nitrogen dioxide	+ oxygen + water vapour	→	**nitric acid**
acidic oxides	atmosphere		acid rain

- Typical pH of acid rain is **4** which is **1000 times more acidic than pure water (pH 7).**



(C) REDUCING AIR POLLUTION CAUSED BY MOTOR VEHICLES

(a) Fuels for motor vehicles such as petrol and diesel contain **hydrocarbons**. Hydrocarbons are compounds that contain **carbon** and **hydrogen** only. Octane (C_8H_{18}) is an example of a hydrocarbon found in petrol.

(b) In the presence of excess oxygen, hydrocarbons undergo **complete** combustion to produce **carbon dioxide** and **water vapour** and release heat.

Example: $2C_8H_{18}(g) + 25O_2(g) \rightarrow 16CO_2(g) + 18H_2O(g)$

(c) In limited supply of oxygen, **carbon particles** (in the form of soot) and a toxic gas, **carbon monoxide**, are produced. This is called **incomplete** combustion.

Examples: $2C_8H_{18}(g) + 17O_2(g) \rightarrow 16CO(g) + 18H_2O(g)$
$2C_8H_{18}(g) + 9O_2(g) \rightarrow 16C(s) + 18H_2O(g)$

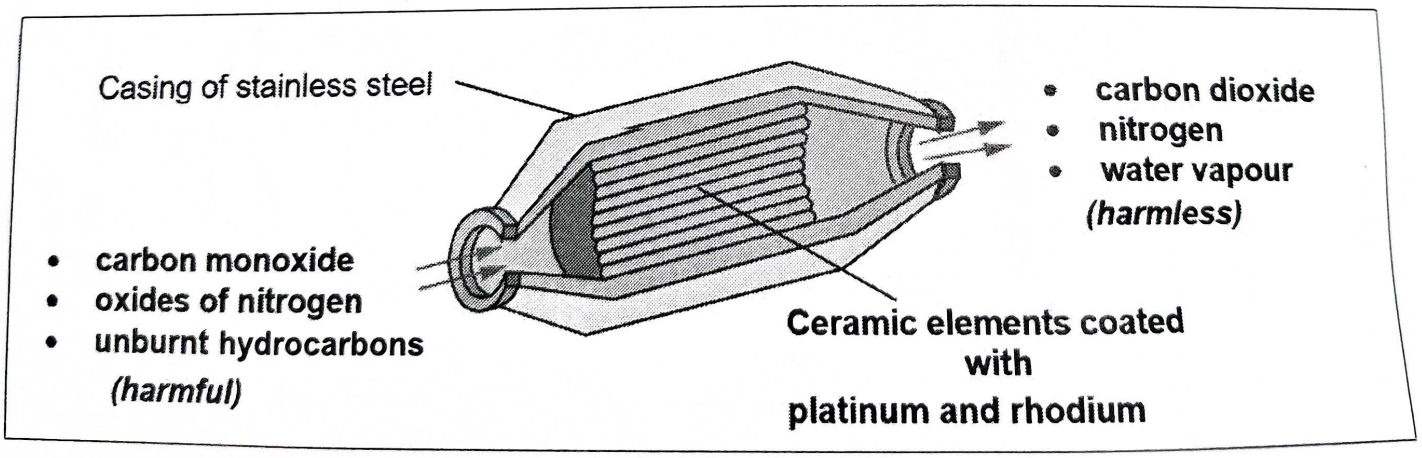
(d) In the vehicle engine, **nitrogen** and **oxygen** in the air react at high temperature. **Nitrogen monoxide** and **nitrogen dioxide** are produced.

Equations: $N_2(g) + O_2(g) \rightarrow 2NO(g)$
$2NO(g) + O_2(g) \rightarrow 2NO_2(g)$

(e) Hence, the exhaust gases from motor vehicles contain harmful **carbon monoxide**, **oxides of nitrogen** and **unburnt hydrocarbons.**

(f) To reduce air pollution, catalytic converters are attached to the motor vehicle exhaust systems.

(g) They contain **platinum** and **rhodium** as catalysts.



Catalytic converter

(h) When hot exhaust gases are passed over the catalyst, **redox** reactions take place. The harmful gases are converted to harmless gases.

(i) Carbon monoxide is **oxidised** to form CO_2.

Equation: $\mathbf{2CO(g) + O_2(g) \rightarrow 2CO_2(g)}$

(ii) Oxides of nitrogen are **reduced** to form N_2.

e.g. Nitrogen monoxide is **reduced** to form N_2.

Equation: $\mathbf{2NO(g) + 2CO(g) \rightarrow 2CO_2(g) + N_2(g)}$

e.g. Nitrogen dioxide is **reduced** to form N_2.

Equation: $\mathbf{2NO_2(g) + 4CO \rightarrow 4CO_2(g) + N_2(g)}$

(iii) Unburnt hydrocarbons such as octane C_8H_{18} are **oxidised** to form CO_2 and H_2O.

Equation: $\mathbf{2C_8H_{18}(g) + 25O_2(g) \rightarrow 16CO_2(g) + 18H_2O(\mathit{l})}$

(i) <u>Other measures to reduce air pollution by motor vehicles</u>

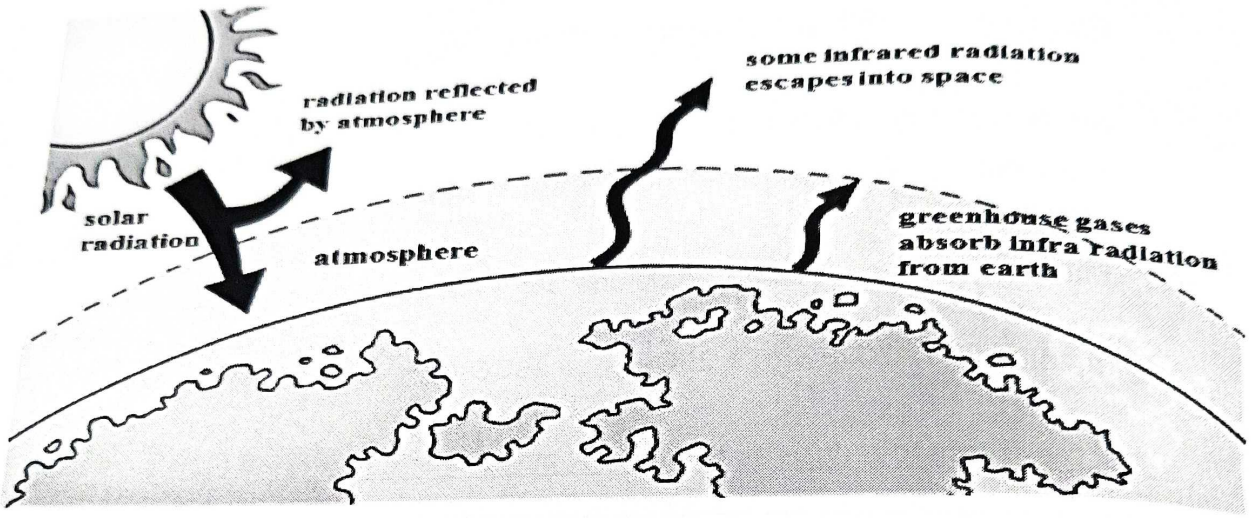
Measure	Effect
Use new materials such as lightweight alloys (instead of steel) to make car bodies.	Less fuel is needed to power lighter car bodies.
Use clean fuels, such as hydrogen.	The products of combustion are harmless. e.g. When hydrogen burns, only water is produced.
Use electric cars.	Battery-powered cars reduce exhaust gas emissions

(D) GLOBAL WARMING & THE CARBON CYCLE

1. Global warming

(a) Some atmospheric gases trap heat from the sun, preventing its loss by radiation to outer space. This process that produces a warming effect is called the **greenhouse effect**. This process is important in **keeping the Earth's surface at a comfortable temperature.**

(b) Some pollutants are trapping an excessive amount of heat in the atmosphere. This is producing a slow increase in temperature. This increase in temperature is called **global warming**.



(c) Two major greenhouses gases are **carbon dioxide** and **methane**.

- The rise in carbon dioxide is due to the increase in the use and **burning of fossil fuels**.
- The increase in methane is believed to be mainly due to increased **bacterial decay of vegetation** due to human activities such as destruction of forest and increased farming of rice fields.

(d) Consequences of the increase in global warming

(1) **Melting of polar ice caps** causes ocean levels to rise and **flooding** of low-lying land.

(2) More **extreme weather events**. More rainfall in some areas and spread of deserts / droughts in other areas. This will cause a decrease in food crops, leading to possible **famine**.

2. Carbon Cycle

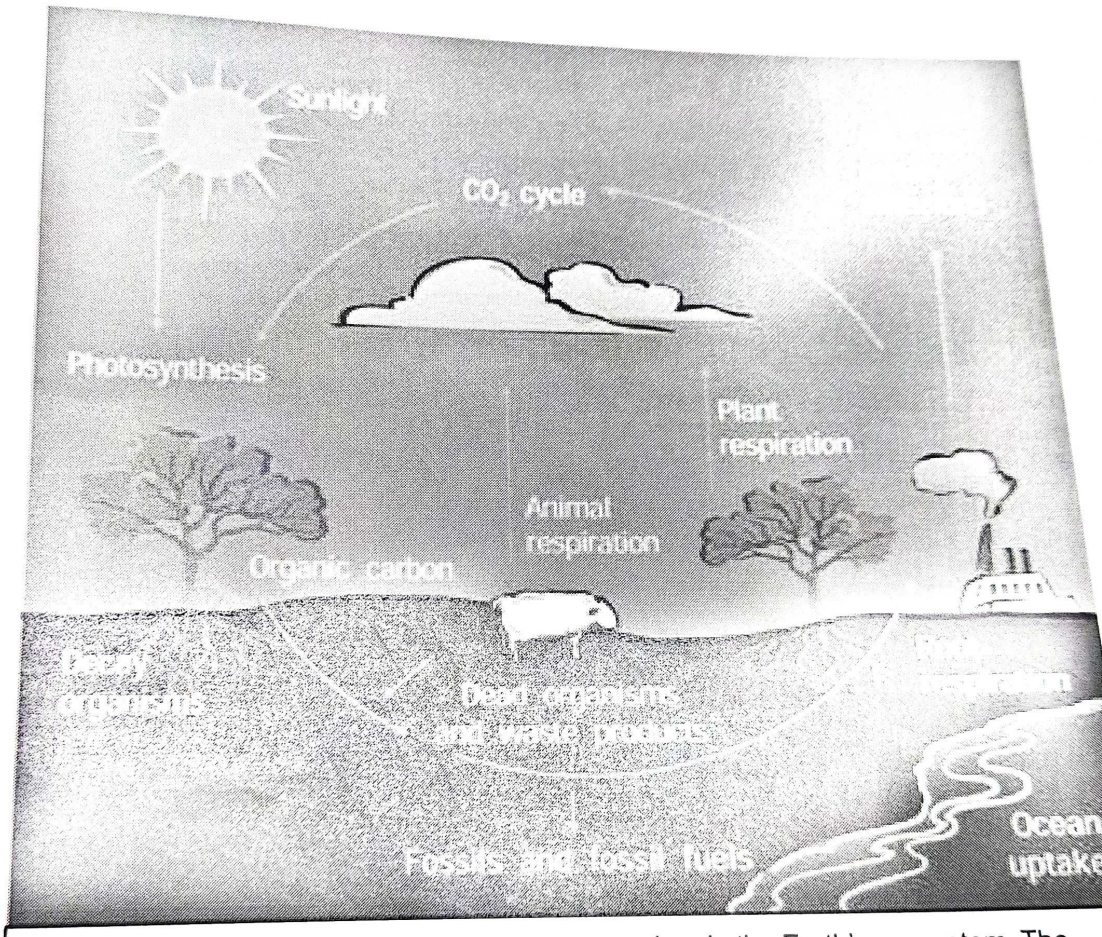
(a) Although the atmosphere contains **0.03 %** of carbon dioxide, this is about 740 billion tonnes of carbon.

(b) This huge reservoir of carbon is continually removed from and returned to the atmosphere by a variety of processes.

(c) To **maintain a constant amount** of atmospheric carbon dioxide:

Rate of removal of carbon dioxide = Rate of return of carbon dioxide

(d) The mechanism that maintains the level of carbon dioxide in the atmosphere is called the **carbon cycle**.



The carbon cycle is the circulation of the element carbon in the Earth's ecosystem. The carbon cycle regulates the amount of carbon dioxide in the Earth's ecosystem.

(e) **How is carbon dioxide produced?**

1. Respiration
   All living things (plants and animals) respire. During respiration, the carbohydrates in food are converted into **carbon dioxide** and **water vapour**.
   Energy is released during respiration.

   Equation: $C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O$

2. Combustion of fossil fuels
   When fossil fuels such as coal, petroleum and natural gas (contains mainly methane) are burnt, carbon dioxide is produced.
   Energy is released during combustion.

   Equation for complete combustion of methane:
   $CH_4(g) + 2O_2(g) \rightarrow CO_2(g) + 2H_2O(g)$

3. Bacterial decay
   When plants and animals die, their bodies are broken down by bacteria.
   Carbon dioxide is produced in the process.

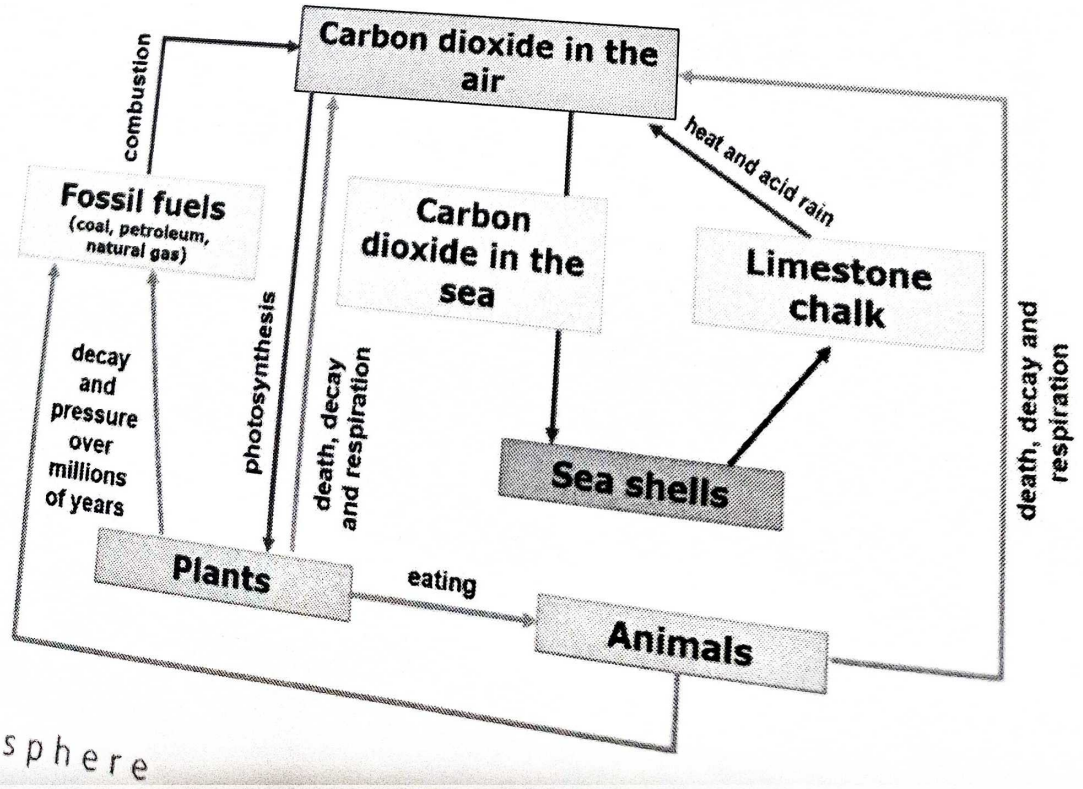
(f) **How is carbon dioxide removed from the atmosphere?**

1. Photosynthesis
   Plants are essential as they help to **remove** carbon dioxide.
   During photosynthesis, **carbon dioxide** and **water** are converted into **glucose** and **oxygen** in the presence of sunlight.

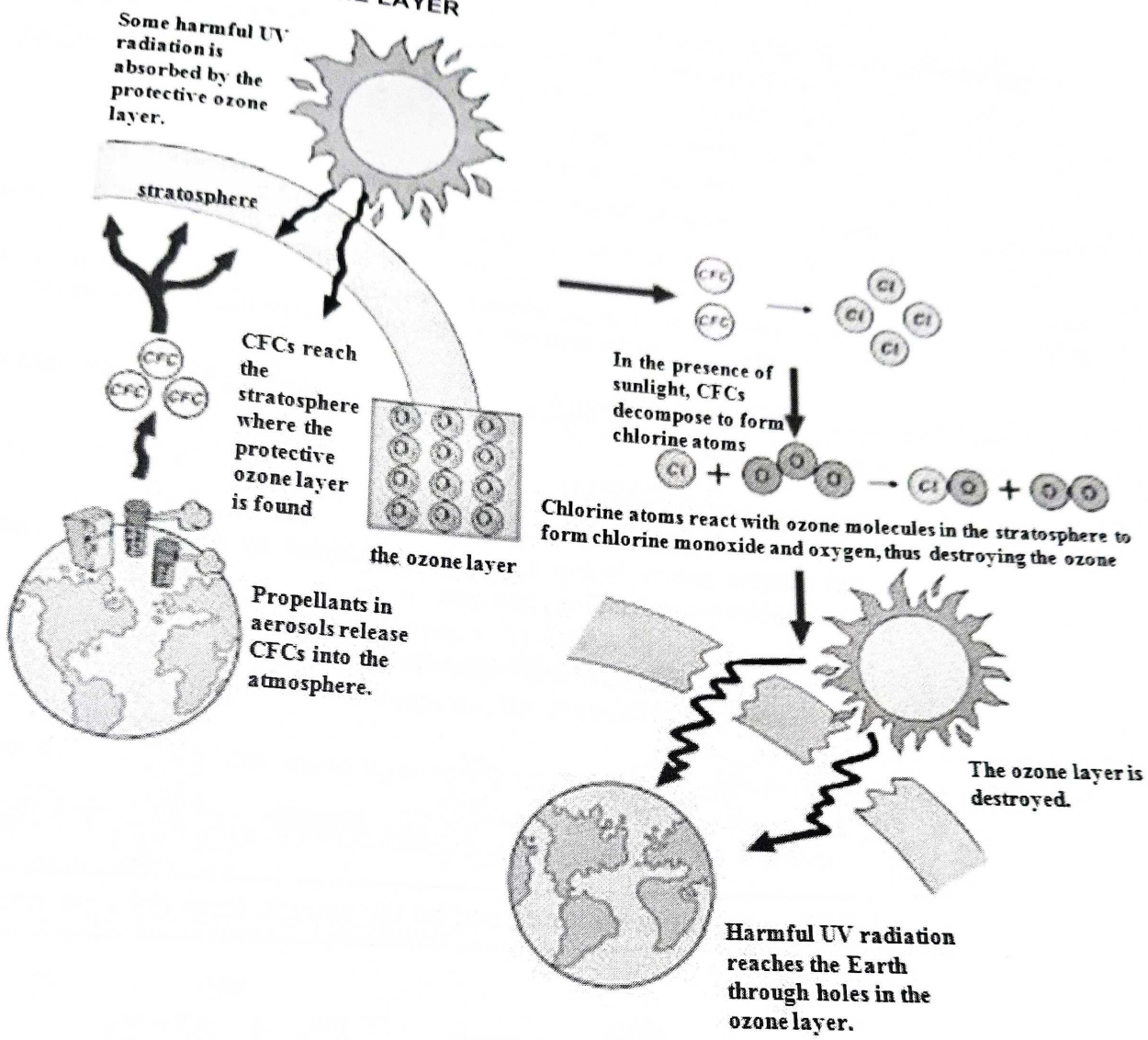
   Equation: $6CO_2 + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$

2. Ocean Uptake

Oceans are very large reservoirs or 'sinks' for carbon dioxide. Much of the dissolved carbon dioxide in the oceans is used by plants in photosynthesis or converted to calcium carbonate in the form of shells and skeletons of marine organisms.



(E) **DEPLETION OF OZONE LAYER**



(a) *The Earth is surrounded by a layer of* **ozone** gas at about 40 km above land surface.

(b) *The ozone layer protects the Earth's surface from excessive harmful* **ultraviolet rays** from the *sun.*

(c) *The ozone layer is being destroyed by* **chlorine** atoms produced from **chlorofluorocarbons** *(CFCs) molecules.*

(d) What are CFCs?

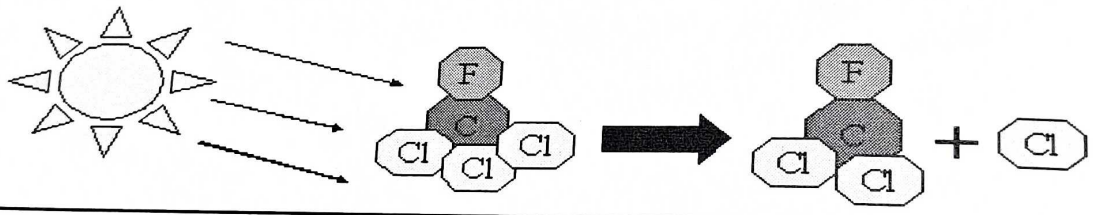
- CFCs are compounds containing **chlorine**, **fluorine** and **carbon**.
- Two important examples have molecular formulae **$\underline{CFCl_3}$** and **$\underline{CF_2Cl_2}$**.
- Sources of CFCs
  - aerosol propellants
  - coolants fluids for refrigerators and air-conditioners
- These compounds are **gases** at room conditions and can be easily made into liquid at a small pressure.
- CFCs are not broken down in the ground-level atmosphere and over some years their molecules rise up and diffuse high into the atmosphere.

(e) High up in the atmosphere, the CFC molecules are **decomposed** by **ultraviolet light** from sun into reactive **chlorine** atoms.

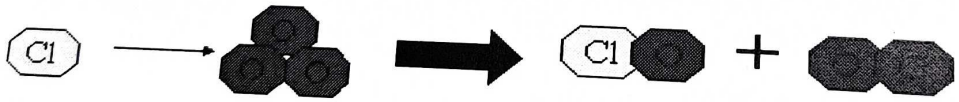
Example: $CFCl_3 \xrightarrow{\text{UV rays}} CFCl_2 + Cl$

The chlorine atoms destroy the ozone molecules by reacting with them to form **chlorine monoxide** and **oxygen gas**.

Equation: $Cl(g) + O_3(g) \rightarrow ClO(g) + O_2(g)$



CFC molecule is decomposed by UV rays to form chlorine atom



Chlorine atom reacts with ozone to form chlorine monoxide and oxygen, resulting in a loss of ozone.

(f) One chlorine atom can destroy up to 10 000 ozone molecules. Why?

Chemical Equations:

Step 1: $Cl + O_3 \rightarrow ClO + O_2$
Step 2: $ClO + O \rightarrow Cl + O_2$

- In step 1, the reactive chlorine atom (Cl) formed will react with an ozone molecule to form **chlorine monoxide** and **oxygen** gas. Hence, destroying the ozone molecule.
- In step 2, the chlorine monoxide formed can react with a reactive oxygen atom (formed when UV breaks down the oxygen molecule into single oxygen atoms), regenerating chlorine atom.
- Hence, the cycle of step 1 and step 2 can be repeated continuously with one chlorine atom destroying thousands of ozone molecules.

Step 1: $Cl + O_3 \rightarrow ClO + O_2$
Step 2: $ClO + O \rightarrow Cl + O_2$

and again ...

Step 1: $Cl + O_3 \rightarrow ClO + O_2$
Step 2: $ClO + O \rightarrow Cl + O_2$
and again... for thousands of times.

(g) The destruction of the ozone layer enables **excessive** UV light to reach the Earth's surface.

(h) Effects of exposure to excessive UV radiation due to ozone depletion:

- causes **skin** cancer
- causes eye disease such as **cataract**
- damages **food crops**

(i) Solution: To stop manufacturing and ban the use of **CFCs**.

Quick Check

1 Which atmospheric pollutant can be removed by being reduced in a redox reaction?

A carbon monoxide in a catalytic converter

B nitrogen monoxide in a catalytic converter

C unburnt hydrocarbons in a catalytic converter

D sulfur dioxide from flue gases by reaction with calcium carbonate

2 Which reaction takes place when combustion pollutants are removed in a catalytic converter?

A $2C + 2NO \rightarrow N_2 + 2CO$

B $2CO + 2NO \rightarrow 2CO_2 + N_2$

C $CO + NO_2 \rightarrow NO + CO_2$

D $CO_2 + NO \rightarrow CO + NO_2$

3 Which process removes carbon dioxide from the atmosphere?

A photosynthesis

B respiration

C bacterial decay

D combustion of fossil fuels

4 Which pair of gases are involved in the formation of acid rain?

A methane and nitrogen monoxide

B carbon monoxide and carbon dioxide

C nitrogen dioxide and carbon monoxide

D nitrogen dioxide and sulfur dioxide

5 Which is true about complete combustion of fuels?

A A toxic gas can be produced.

B The products can be carbon particles and water.

C It takes place in the presence of excess oxygen.

D Some unburnt hydrocarbons will be left behind.

Ans: (1) B, (2) B, (3) A, (4) D, (5) C

	Answers	Explanation
1	B	(A) The catalytic converter **oxidises** the harmful carbon monoxide into harmless carbon dioxide. (B) In the converter, the oxides of nitrogen (e.g. nitrogen monoxide) are **reduced** to harmless nitrogen gas.
2	B	(B) $2CO + 2NO \rightarrow 2\mathbf{CO_2} + \mathbf{N_2}$ The products of the reaction in the catalytic converter are **harmless substances** CO_2 and N_2. Pollutants like CO, NO and NO_2 should not be produced.
3	A	(A) During photosynthesis, **carbon dioxide** and **water** are converted into **glucose** and **oxygen** in the presence of sunlight. Equation: $6\mathbf{CO_2} + 6H_2O \rightarrow C_6H_{12}O_6 + 6O_2$ Hence photosynthesis **removes CO_2** from the atmosphere. (B) During respiration, the carbohydrates in food are converted into **carbon dioxide** and **water vapour**. Energy is released during respiration. Equation: $C_6H_{12}O_6 + 6O_2 \rightarrow 6\mathbf{CO_2} + 6H_2O$ (C) When plants and animals die, their bodies are broken down by bacteria. **Carbon dioxide is produced** in the process. (D) When fossil fuels such as coal, petroleum and natural gas (contains mainly methane) are burnt, **carbon dioxide is produced**. Equation for complete combustion of methane: $CH_4(g) + 2O_2(g) \rightarrow \mathbf{CO_2}(g) + 2H_2O(g)$
4	D	(D) Nitrogen dioxide and sulfur dioxide Nitrogen dioxide reacts with oxygen and the water vapour in the air to form nitric acid. Equation: $4NO_2(g) + O_2(g) + 2H_2O(l) \rightarrow 4HNO_3(aq)$ Sulfur dioxide in the air reacts with water to form sulfurous acid, which is slowly oxidised in air to form sulfuric acid. Equations: $SO_2(g) + H_2O(l) \rightarrow H_2SO_3(aq)$ $2H_2SO_3(aq) + O_2(g) \rightarrow 2H_2SO_4(aq)$
5	C	(C) In the presence of **excess oxygen**, hydrocarbons undergo **complete** combustion to produce **carbon dioxide** and **water vapour** and release heat. Example: $2C_8H_{18}(g) + 25O_2(g) \rightarrow 16CO_2(g) + 18H_2O(g)$