4.1 THE GASEOUS STATE

Learning outcomes
Candidates should be able to:

1. explain the origin of pressure in gas in terms of collisions between gas molecules and the wall of the container
2. understand that ideal gases have zero particle volume and no intermolecular forces of attraction
3. state and use the ideal gas equation $pV = nRT$ in calculations, including in the determination of M_r

Initial assessment

1. Describe the states of matter (solids, liquids and gases) in terms of the proximity (closeness), arrangement and motion of particles.
2. How does the volume of a gas change when the temperature is changed at constant pressure and the pressure is changed at constant temperature?
3. Describe the changes that occur in the closeness and motion of the particles when:
   - a solid changes to a liquid
   - a liquid changes to a gas.

The three states of matter

Gases have no fixed shape or volume.
Gas particles:

are far apart, therefore gases can be compressed
are randomly arranged
can move freely from place to place, in all directions.

Liquids take the shape of the container they occupy.
Liquid particles:

are close together, so liquids have a fixed volume and can only be compressed slightly
are mostly arranged randomly
have limited movement from place to place, in all directions.

Solids have a fixed shape and volume.
Solid particles:

are touching each other, so solids cannot be compressed
are usually in a regular arrangement
cannot change positions with each other: they can only vibrate.

1. There are three different compounds A, B and C kept in three different cylinders. All of them exist in the three different states of matter. The intermolecular force in compound B is the highest while compound A has the lowest intermolecular force between the molecules. Which of the following identifications is correct?
   a. A: gas; B: liquid; C: solid
   b. A: gas; B: solid; C: liquid
   c. A: solid; B: liquid; C: gas
   d. A: solid; B: liquid; C: gas

2. Sodium chloride, water and air represent three states of matter – solid, liquid and gas.
Which row is correct?

	sodium chloride	water	air
A	particles held in rigid structure	can easily be compressed	can easily be compressed
B	particles stationary	particles move	cannot easily be compressed
C	particles stationary	particles stationary	particles move
D	resistant to change of shape	cannot easily be compressed	can easily be compressed

The kinetic theory of gases

The idea that molecules in gases are in constant movement is called the **kinetic theory of gases**. This theory makes certain assumptions:

- the gas molecules move rapidly and randomly
- the distance between the gas molecules is much greater than the diameter of the molecules, so the volume of the molecules is negligible (hardly any volume).
- there are no intermolecular forces of attraction or repulsion between the molecules
- all collisions between particles are elastic: this means no kinetic energy is lost in collisions (kinetic energy is the energy associated with moving particles)
- the temperature of the gas is related to the average kinetic energy of the molecules.

A theoretical gas that fits this description is called an **ideal gas**. In reality, the gases don't fit this description exactly, although they may come very close. We call these gases **real gases**.

Noble gases with small atoms, such as helium and neon, come close to ideal gas behaviour. This is because the intermolecular forces are so small.

Explain why the intermolecular forces in a sample of helium and neon are very small.

Ideal gases have zero particle volume and no intermolecular forces of attraction.

1. Which statement about ideal gases is correct?

A Ideal gases have finite particle volume and no intermolecular forces of attraction.
B Ideal gases have finite particle volume and weak intermolecular forces of attraction.
C Ideal gases have zero particle volume and no intermolecular forces of attraction.
D Ideal gases have zero particle volume and weak intermolecular forces of attraction.

2. Which assumptions are made about ideal gases?

1 Ideal gases contain molecules with no masses.
2 Ideal gases contain molecules with no volume.
3 Ideal gases have zero intermolecular forces.

A 1, 2 and 3 B 1 and 3 C 2 and 3 D 1 and 2

Limitations of the ideal gas laws

Scientists have taken accurate measurements to show how the volumes of gases change with temperature and pressure. These show us that gases do not always behave exactly as we expect an ideal gas to behave. This is because real gases do not always obey the kinetic theory in two ways:

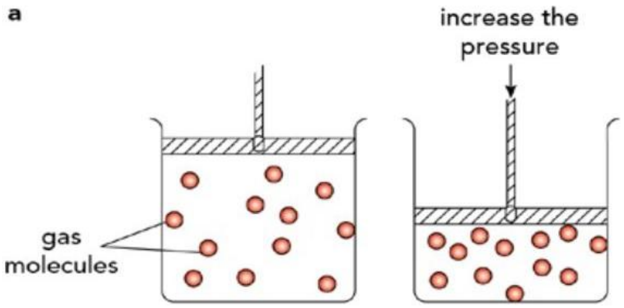
- there is not zero attraction between the molecules
- we cannot ignore the volume of the molecules themselves.

These differences are especially noticeable at very **high pressures and very low temperatures**. Under these conditions:

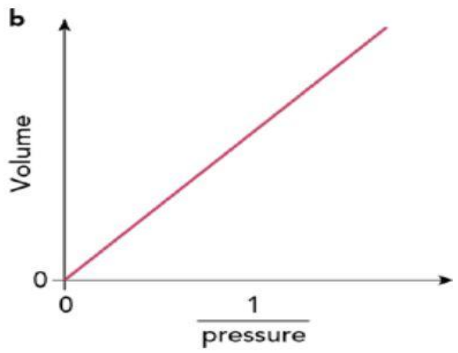
- the molecules are close to each other
- the volume of the molecules is not negligible compared with the volume of the container
- there are instantaneous dipole-induced dipole forces or permanent dipole-permanent dipole forces of attraction between the molecules
- attractive forces pull the molecules towards each other and away from the walls of the container
- the pressure is lower than expected for an ideal gas
- the effective volume of the gas is smaller than expected for an ideal gas

The pressure of a gas is due to collisions between the gas molecules and the walls of the container.

Gases in a container exert pressure. This is because the gas molecules are constantly hitting the walls of the container. If we decrease the volume of a gas (at constant temperature) the molecules are squashed closer together and hit the walls of the container more often. So, the pressure of the gas increases.



A graph of the volume of gas plotted against the inverse of pressure gives a proportional relationship (as shown by the straight line in Figure). We say that the volume is **inversely proportional** to the pressure.



Learners explore the effects of changing the temperature, volume and gas particle added to a vessel in this simulation: [Gas Law Simulator (utexas.edu)]

3. Under which conditions will nitrogen behave most like an ideal gas?

	temperature	Pressure
A	low	high
B	high	low
C	low	low
D	high	high

4. Each of the substances shown is gaseous.
Which substance is most likely to show ideal behaviour in the conditions shown?

	substance	temperature/ K	pressure/ Pa
A	carbon dioxide	250	1.00×10^5
B	hydrogen chloride	1000	1.00×10^6
C	nitrogen	1000	1.00×10^5
D	oxygen	250	1.00×10^6

5. Which gas would behave most like an ideal gas under room conditions?

A helium **B** nitrogen **C** ammonia **D** krypton

6. Which substance shows the greatest deviation from the properties of an ideal gas under room conditions?

A CO_2(g) B H_2(g) C Ne(g) D NH_3(g)

7. What changes in conditions or molecular properties make it more likely that gases approach ideal behaviour?

A higher pressure B lower temperature
C more polar molecules D weaker intermolecular forces

1. Nitrogen, N_2, is a gas at room temperature and pressure. Neither CO nor N_2 is an ideal gas.
(i) State two assumptions that are made about the behaviour of particles in an ideal gas. [2]

(ii) Explain why N_2 does not behave as an ideal gas at very high pressures. [2]

2. Explain why N_2(g) behaves more like an ideal gas than CO(g) does at 20.0°C and 101kPa.
3. State and explain the conditions at which krypton behaves most like an ideal gas. [2]

The general gas equation (ideal gas equation)

The ideal gas equation **pV = nRT** shows the relationship between pressure, volume, temperature and number of moles of gas.

p is the **pressure in pascals, Pa** (a pressure of 101325 pascals = 1.0 atmosphere pressure.)

V is the **volume** of gas in **cubic metres, m^3** ($1\ m^3 = 1000\ dm^3$)
n is the **number of moles** of gas ($n = m/M_r$)
R is the **gas constant,** which has a value of **$8.31\ J\ K^{-1}\ mol^{-1}$**
T is the **temperature** in **kelvin, K.** (To change °C to kelvin, add 273 to the Celsius (°C) temperature.)

If you substitute the pressure in kPa in the equation **pV = nRT**, the volume of gas calculated will be in dm^3. If you substitute the pressure in Pa in the equation **pV = nRT**, the volume of gas calculated will be in m^3.

4. Calculate the volume taken up by 1 mol of an ideal gas at room temperature and pressure (25°C and 1.01×10^5Pa). (ans = 0.0245 m^3)

5. How many moles of ideal gas are there in the following volumes?
a. 2.8dm^3 of gas at a pressure of 1.01×10^5Pa and a temperature of 10°C. (ans = 0.120 moles)

b. 54dm^3 of gas at a pressure of 5.0×10^5Pa and a temperature of 600°C. (ans = 3.72 moles)

6. Calculate the amount, in mol, of pure nitrogen gas which occupies 100cm^3 at 101kPa and 20.0°C.
Show your working.
Assume nitrogen behaves as an ideal gas. (ans = 0.00415 moles) [3]

7. Calculate the volume occupied by 272 g of methane at a pressure of 250 kPa and a temperature of 54°C. (**R** = 8.31 J K^{-1} mol^{-1}; $\mathbf{M}_r$ methane = 16.0) (ans = 184.78 dm^3)

8. 2.00g of krypton gas, Kr(g), is placed in a sealed $5.00dm^3$ container at 120°C.
Calculate the pressure, in Pa, of Kr(g) in the container.
Assume Kr(g) behaves as an ideal gas.
Show your working. (ans $=1.56 \times 10^4$) [3]

8. The ideal gas equation below summarises the gas laws.
pV=nRT
Which statement below is correct?

A. There exist intermolecular forces of attraction between gas molecules.
B. Ideal gas molecules will collide inelastically upon impact with each other.
C. One mole of an ideal gas occupies the same volume under the same conditions of temperature and pressure.
D. The volume of a given mass of an ideal gas is doubled if its temperature Is raised from 25°C to 50°C.

9. The general gas equation can be used to calculate the value of the $\mathbf{M_r}$ of a gas.
For a sample of a gas of mass m grams, which expression will give the value of $\mathbf{M_r}$?

A $M_r = \dfrac{mRT}{pV}$ **B** $M_r = \dfrac{pVRT}{m}$ **C** $M_r = \dfrac{mpV}{RT}$ **D** $M_r = \dfrac{pV}{mRT}$

10. A pure sample of a gas has a density of 2.62 g dm^{-3} at 101 000 Pa and 25 °C. The gas behaves ideally under these conditions.
Which expression gives the M_r of the gas?

A $\dfrac{101000 \times 0.001}{2.62 \times 8.31 \times 25}$

B $\dfrac{101000 \times 0.001}{2.62 \times 8.31 \times 298}$

C $\dfrac{2.62 \times 8.31 \times 25}{101000 \times 0.001}$

D $\dfrac{2.62 \times 8.31 \times 298}{101000 \times 0.001}$

11. 1.8 g of water, heated to 227°C in a sealed container, turns to steam with a pressure of 200 kPa.
What is the approximate volume of the container?

A $9 \cdot 10^{-4} m^3$ **B** $2 \times 10^{-3} m^3$ **C** $2\ m^3$ **D** $8 \times 10^7 m^3$

12. In this question it should be assumed that nitrogen behaves as an ideal gas under the conditions stated.
Which volume is occupied by 1.00 g of nitrogen at 50.0 °C and at a pressure of 120 kPa?

A 0.124 dm^3 **B** 0.799 dm^3 **C** 1.60 dm^3 **D** 22.4 dm^3

13. The volume of a vessel is $1.20 \times 10^{-3}\ m^3$. It contains pure argon at a pressure of 1.00×10^5 Pa, and at a temperature of 25.0°C. Under these conditions it can be assumed that argon behaves as an ideal gas.
Which mass of argon does it contain?

A 0.0485 g B 1.93 g C 10.4 g D 23.0 g

14. The gas laws can be summarised in the ideal gas equation.
$pV = nRT$
0.960 g of oxygen gas is contained in a vessel of volume $7.00 \times 10^{-3}\ m^3$ at a temperature of 30 °C.
Assume that the gas behaves as an ideal gas.
What is the pressure in the vessel?

A 1.07 kPa B 2.14 kPa C 10.8 kPa D 21.6 kPa

15. A sample of argon gas has a mass of 0.20 g, at a pressure of 100 000 Pa and a temperature of 12 °C.
Which volume does the gas occupy?

A $1.2 \times 10^{-4}\ cm^3$ **B** 5.0 cm^3 **C** 59 cm^3 **D** 119 cm^3

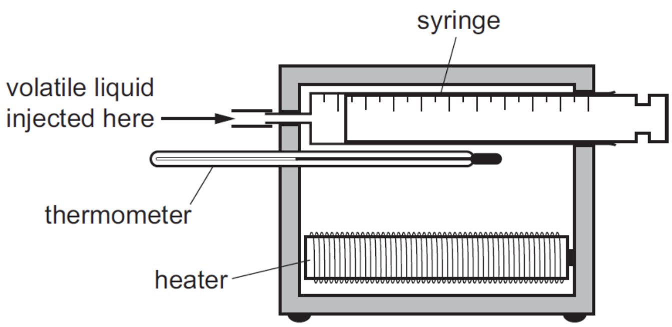
16. A weather balloon is filled with 12.0 kg helium. The weather balloon reaches a height of 20 km, the pressure inside the balloon is 6000 Pa and the temperature is 216 K.
What is the volume of the weather balloon at this height, correct to three significant figures?

A 897 dm^3 **B** 1790 dm^3 **C** 897 000 dm^3 **D** 1 790 000 dm^3

17. 1.00 g of nitrogen gas is stored in a 2.00 dm^3 vessel at 40.0 °C.
What is the pressure in the vessel?

A 5940 Pa B 11 900 Pa C 46 400 Pa D 92 900 Pa

18. The diagram shows the apparatus used to find the relative molecular mass of a volatile liquid.
When 0.10 g of a volatile liquid is injected into the syringe, all of the volatile liquid evaporates and the volume increases by 85 cm^3.
The heater maintains a temperature of 400 K and the experiment is carried out at a pressure of 101 300 Pa.



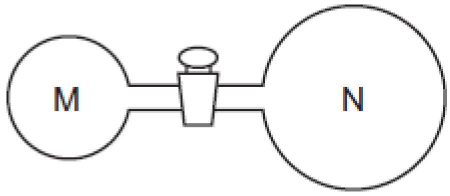
If the vapour of the volatile liquid behaves as an ideal gas, which expression can be used to calculate the relative molecular mass of the liquid?

A Mr = (85 x 101 300) / (0.10 x 8.31 x 400)
B Mr = (85 x 101.3) / (0.10 x 8.31 x 400)
C Mr = (0.10 x 8.31 x 400) / (85 x 10^{-6} x101 300)
D Mr = (0.10 x 8.31 x 400) / (85 x 10^{-6} x 101.3)

19. Flask Q contains 5 dm^3 of helium at 12 kPa pressure. Flask R contains 10 dm^3 of neon at 6 kPa pressure.
What is the final pressure if the flasks are connected at constant temperature?

A 8 kPa **B** 9 kPa **C** 10 kPa **D** 11 kPa

20. Two glass vessels, M and N, are connected by a closed valve.



M contains helium at 20 ^{0}C at a pressure of 1 x 10^5 Pa. N has been evacuated, and has three times the volume of M. The valve is opened and the temperature of the whole apparatus is raised to 100 ^{0}C.
What is the final pressure in the system?

A 3.18 x 10^4Pa
B 4.24 x 10^4Pa
C 1.25 x 10^5Pa
D 5.09 x 10^5Pa

21. What is the density of a sample of fluorine gas at 32 °C and 100 000 Pa? Assume fluorine behaves as an ideal gas under these conditions.

A 1.4 g dm^{-3} **B** 1.5 g dm^{-3} **C** 1.6 g dm^{-3} **D** 1.7 g dm^{-3}

9. When 0.08 g of liquid X was vaporised at 100 °C, 23 cm^3 of vapour was formed. The atmospheric pressure was 1.02×10^5 Pa. Calculate the relative molecular mass of liquid X. (**R** = 8.31 J K^{-1} mol^{-1})

22. When an evacuated tube of volume 400 cm^3 is filled with gas at 300 K and 101 kPa, the mass of the tube increases by 0.65 g.
Assume the gas behaves as an ideal gas.
What is the identity of the gas?

A argon **B** helium **C** krypton **D** neon

10. A 3.30 g sample of a Period 3 chloride is heated to 500 K in a sealed flask.
At this temperature, the chloride is a gas of volume 250 cm^3 and the pressure in the flask is 323 kPa.
Use the ideal gas equation **pV** = **nRT** to calculate the **M**r of the Period 3 chloride.
Deduce its formula.

Mr = ... formula of Period 3 chloride = ...[3]

11. (i) Complete Table 1.2 by placing a tick (✓) to show which of the compounds have molecules with an overall dipole moment.

compound	O=C=O	O=S=O	S=C=S	S=C=O
overall dipole moment				

(ii) At 150°C and 103kPa, all of the compounds listed in Table 1.2 are gases.
Under these conditions, 0.284g of one of the compounds occupies a volume of 127cm^3.
Use this information to calculate the Mr of the compound. Hence, identify the compound from those given in Table 1.2.
Show your working.
Mr = ... identity of compound M = ...
(Ans = 76.2; CS_2) [3]

23. In this question you may assume that nitrogen behaves as an ideal gas. One atmosphere pressure = 101 kPa.
Which volume does 1.0 g of nitrogen occupy at 50 ?C and a pressure of 2.0 atmospheres?

A 70 cm^3 **B** 150 cm^3 **C** 470 cm^3 **D** 950 cm^3

24. At a temperature of 2500K and a pressure of 1.00×10^{-4} Pa, a sample of 0.321 g of sulfur vapour has a volume of $2.08 \times 10^6 m^3$.
What is the molecular formula of sulfur under these conditions?

A S **B** S_2 **C** S_4 **D** S_8

25. A solution contains 0.25 g of sulfur dioxide in 1.00 dm^3 of water.
Which volume of sulfur dioxide, measured at 50 °C and a pressure of 1×10^5 Pa, must be added to 1.00 dm^3 of water to produce this solution?

A 0.0162 cm^3 B 0.105 cm^3 C 16.2 cm^3 D 105 cm^3

26. A 200 cm^3 sample of water has an amount of oxygen gas dissolved in it.
This amount of oxygen gas has a volume of 6.00 cm^3 when measured at 1.00×10^5 Pa and 35°C.
What is the concentration of oxygen gas in the water? (You should assume that oxygen behaves as an ideal gas.)

A 2.34×10^{-4} mol dm^{-3}
B 1.17×10^{-3} mol dm^{-3}
C 1.25×10^{-3} mol dm^{-3}
D 1.03×10^{-2} mol dm^{-2}

12. Molten $KClO_3$ reacts with glucose, $C_6H_{12}O_6$.
$4KClO_3 + C_6H_{12}O_6 \rightarrow 6CO_2 + 6H_2O + 4KCl$
$KClO_3$ melts at 630K. At this temperature, both CO_2 and H_2O are gases.
(i) Use the ideal gas equation to calculate the volume, in m^3, of one mole of gas at 630K and 1.00×10^5Pa.
Show your working. Give your answer to 3 significant figures. (ans = 0.0523 m^3)

[1]

(ii) 5.00g of $C_6H_{12}O_6$ reacts completely with molten $KClO_3$.
Use your answer to (i) to calculate the total volume of gas released at 630K and 1.00×10^5Pa in this reaction. (ans = 0.017 m^3)
(If you were unable to answer (i), use 0.0463m^3 in this question. This is not the correct answer to (i).) [2]

13. Glycerol can be used as a starting material in the manufacture of nitroglycerine, $C_3H_5N_3O_9$.
Nitroglycerine decomposes rapidly on heating to form a mixture of gases.
$4C_3H_5N_3O_9(l) \rightarrow 12CO_2(g) + 10H_2O(g) + 6N_2(g) + O_2(g)$
A sample of nitroglycerine decomposes, releasing $1.06 dm^3$ of $O_2(g)$ at 850K and 1.00×10^5Pa.
(i) Calculate the mass of nitroglycerine that decomposes. (ans=13.6 g) [3]

(ii) Calculate the total volume of gas released by this decomposition at 850K and 1.00×10^5Pa. (ans = $0.03 m^3$)[1]

14. 0.144 g of C_{60} is placed in a $100 cm^3$ container of hydrogen gas at a temperature of 20°C and a pressure of 1.00×10^5 Pa.
The container is heated to make the C_{60} and hydrogen gas react. The reaction occurs as shown in the equation.
$C_{60}(s) + xH_2(g) \rightarrow C_{60}H_{2x}(s)$
After the reaction, the container is allowed to cool to 20 °C. The pressure decreases to 2.21×10^4 Pa. All of the C_{60} has reacted.
(i) Name the type of reaction that occurs. [1]

(ii) Calculate the amount, in moles, of C_{60} that reacts.

amount of C_{60} = ... mol [1]

(iii) Calculate the amount, in moles, of hydrogen gas that reacted with the C_{60}.
Show your working.

amount of hydrogen gas = ... mol [3]

(iv) Use your answers from **(c)(ii)** and **(c)(iii)** to deduce the molecular formula of the hydrocarbon, $C_{60}H_{2x}$.
(If you were unable to calculate the amount of hydrogen gas, assume that 0.00240 mol of hydrogen gas reacts. This is **not** the correct value.)
Show your working.

molecular formula = ... [2]

27. In this question you should assume that the gas formed behaves as an ideal gas.
A 1.7 g sample of Mg reacts with 50.0 cm^3 of 2.2 mol dm^{-3} HCl at 303 K and 110 400 Pa.
Which volume of gas is produced, measured under these conditions?

A 1.3 dm^3 B 1.6 dm^3 C 2.5 dm^3 D 5.0 dm^3

28. 10 cm^3 of ethane is burned in 45 cm^3 of oxygen at a pressure of 101 kPa and a temperature of 200 °C. Complete combustion takes place.
What is the total volume of gas present when the reaction is complete, measured under the same conditions?

A 30 cm^3 **B** 50 cm^3 **C** 55 cm^3 **D** 60 cm^3

29. The complete combustion of 2 moles of an alkane produces 665dm^3 of carbon dioxide measured at 400K and 1×10^5Pa.
Carbon dioxide can be assumed to behave as an ideal gas under these conditions.
What is the formula of the alkane?

A C_5H_{12} **B** C_8H_{18} **C** $C_{10}H_{22}$ **D** $C_{20}H_{42}$

30. ‘Black powder’ is a mixture of potassium nitrate, carbon and sulfur. The mixture reacts as shown.

$4KNO_3(s) + 7C(s) + S(s) \rightarrow 3CO_2(g) + 3CO(g) + 2N_2(g) + K_2S(s) + K_2CO_3(s)$

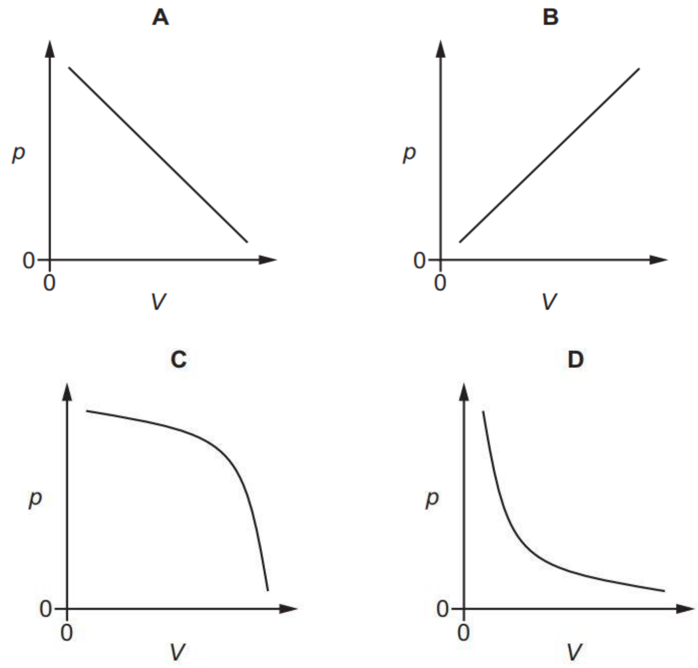
A sealed tube containing black powder has a volume of 10.0 cm^3. When all of the black powder reacts, the reaction causes a pressure of 2×10^6 Pa and a temperature of 2500 K.

The volume of the K_2CO_3 and K_2S produced can be ignored.

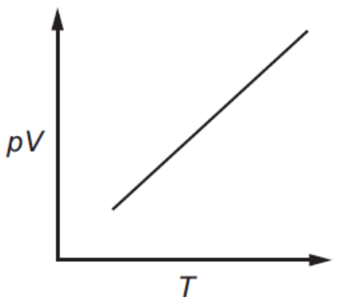
How many moles of KNO_3 are contained in the sealed tube?

A 4.81×10^{-4} **B** 9.63×10^{-4} **C** 1.93×10^{-3} **D** 9.63×10^{-1}

31. Which graph represents the variation of pressure p and volume V of a sample of an ideal gas at constant temperature?



32. A graph of pV against T is shown for a fixed mass of gas. (p = pressure, V = volume and T = temperature in K.)



Which gas gives this graph over the widest range of temperatures and pressures?

A hydrogen, H2
B hydrogen chloride, HC*l*
C hydrogen fluoride, HF
D oxygen, O2

*****This is not a complete note. It is to guide you. It is recommended to study the prescribed textbooks along with this material. *****