Kinetic-Molecular Theory of Gases

The Kinetic-Molecular Theory of Gases

- **Postulate 1:** Gas particles are tiny with large spaces between them. The volume of each particle is so small compared to the total volume of the gas that it is assumed to be zero.

- **Postulate 2:** Gas particles are in constant, random, straight-line motion except when they collide with each other or with the container walls.

- **Postulate 3:** Collisions are ***elastic***, meaning that colliding particles exchange energy but do not lose any energy due to friction. ***Their average kinetic energy remains constant for a given temperature.***

Kinetic Energy and Gas Behavior

- At a given temperature ***T***, all the particles in a gas sample have the ***same average kinetic energy***.

$$\boxed{K.E. = \frac{1}{2}\,\text{mass} \times \text{speed}^2}$$

- As the temperature increases (or decreases), the average speed of the particles increases (or decreases), and so their average kinetic energy increases (or decreases).

Ideal Gas Laws

The Gas Laws

- The gas laws describe the physical behavior of gases in terms of four variables:
  - pressure (*P*)
  - temperature (*T*)
  - volume (*V*)
  - number of moles (*n*)

- An ***ideal gas*** is a gas that exhibits linear relationships among these variables.

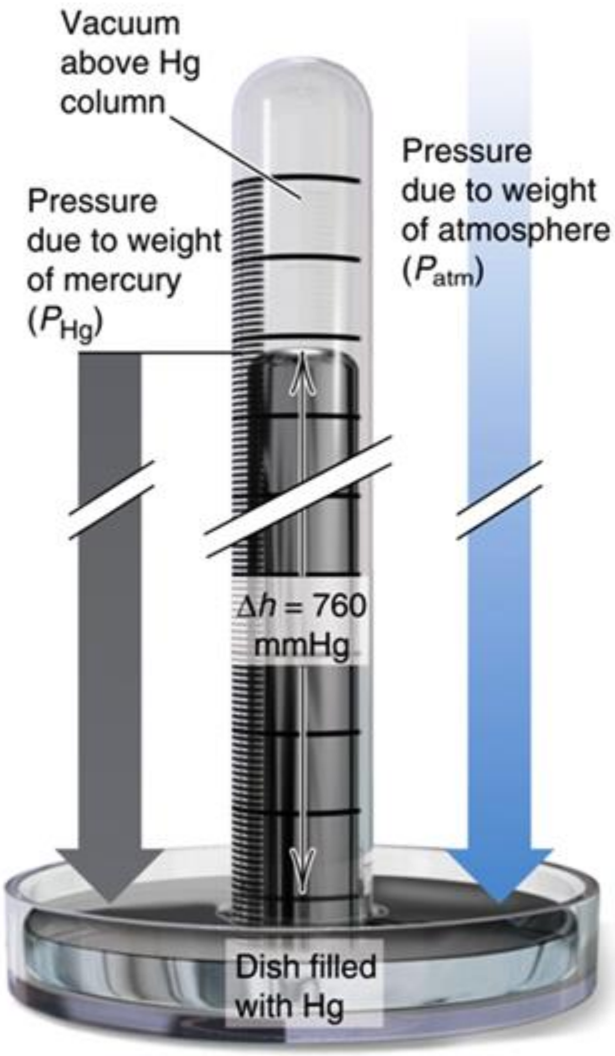
- ***No ideal gas actually exists***, but most simple gases behave nearly ideally at ordinary temperatures and pressures.

Common Units of Pressure

Unit	Normal Atmospheric Pressure at Sea Level and 0°C
pascal (Pa); kilopascal (kPa)	1.01325×10^5 Pa; 101.325 kPa
atmosphere (atm)	1 atm*
millimeters of mercury (mmHg)	760 mmHg*
torr	760 torr*
pounds per square inch (lb/in^2 or psi)	14.7 lb/in^2
bar	1.01325 bar

*This is an exact quantity; in calculations, we use as many significant figures as necessary.

A Mercury Barometer for Measuring Air Pressure



$$\text{Pressure} = \frac{\text{Force}}{\text{Area}}$$

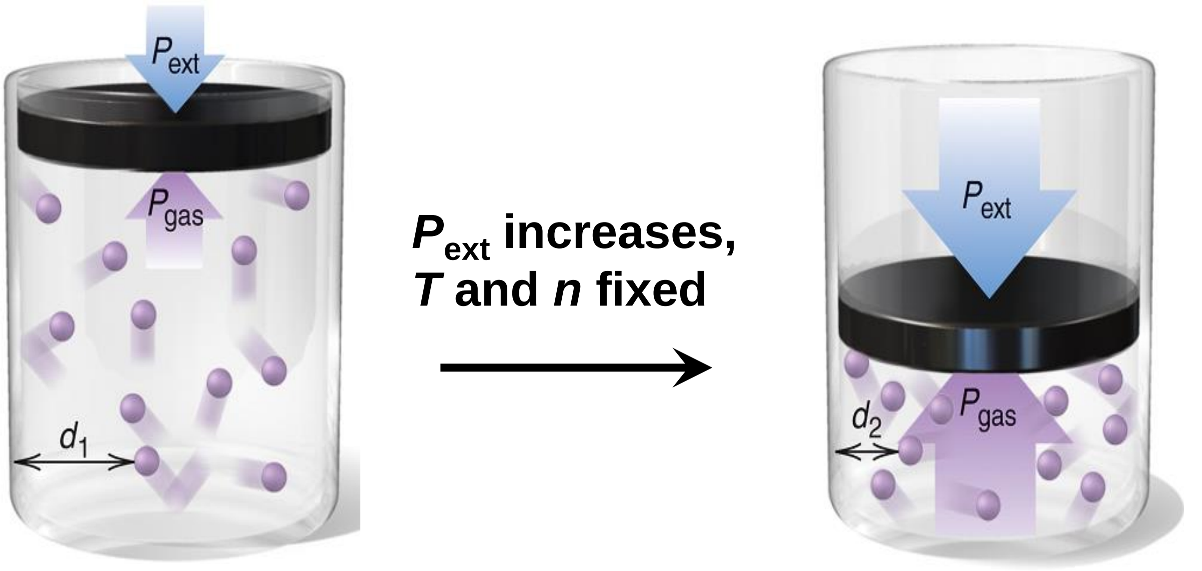
Boyle's Law

- At constant temperature, the volume occupied by a fixed amount of gas is ***inversely*** proportional to the external pressure.

$$V \propto \frac{1}{P}$$ or $PV = \text{constant}$ or $P_1V_1 = P_2V_2$

$V = k \cdot \frac{1}{P}$

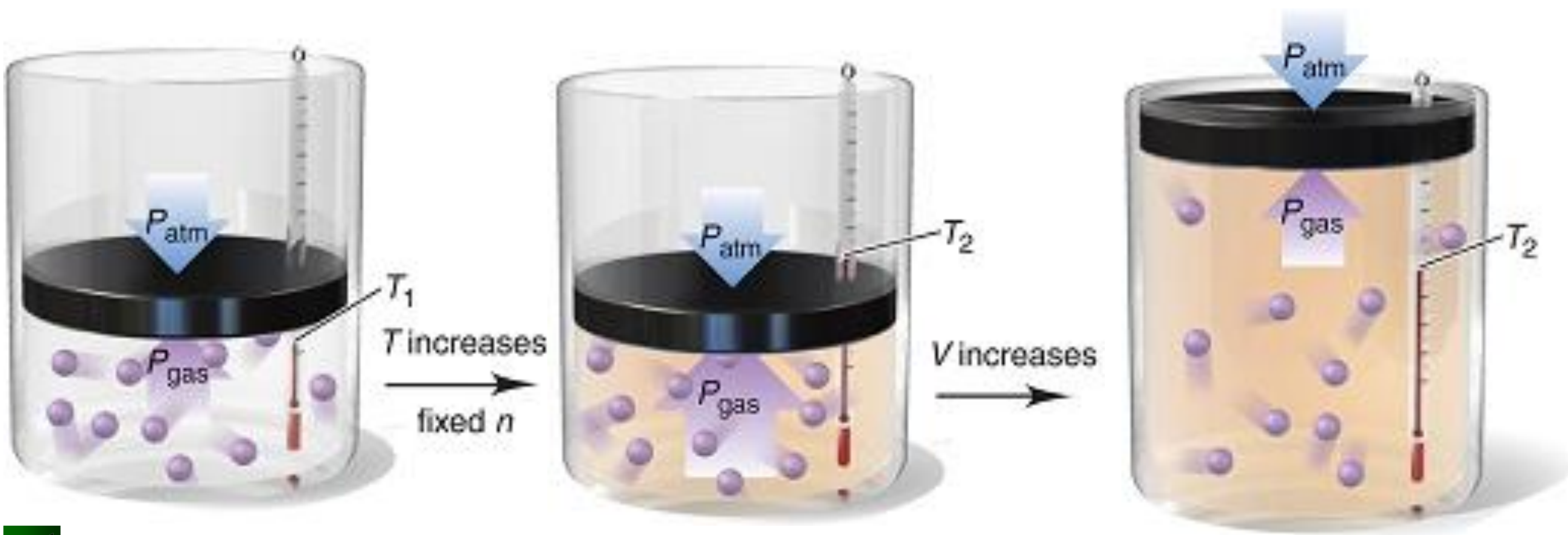
$PV = k$



Charles's Law

- At constant pressure, the volume occupied by a fixed amount of gas is ***directly*** proportional to its absolute (Kelvin) temperature.

$V \propto T$ **or** $\frac{V}{T} = \text{constant}$ **or** $\frac{V_1}{T_1} = \frac{V_2}{T_2}$



Pressure Law

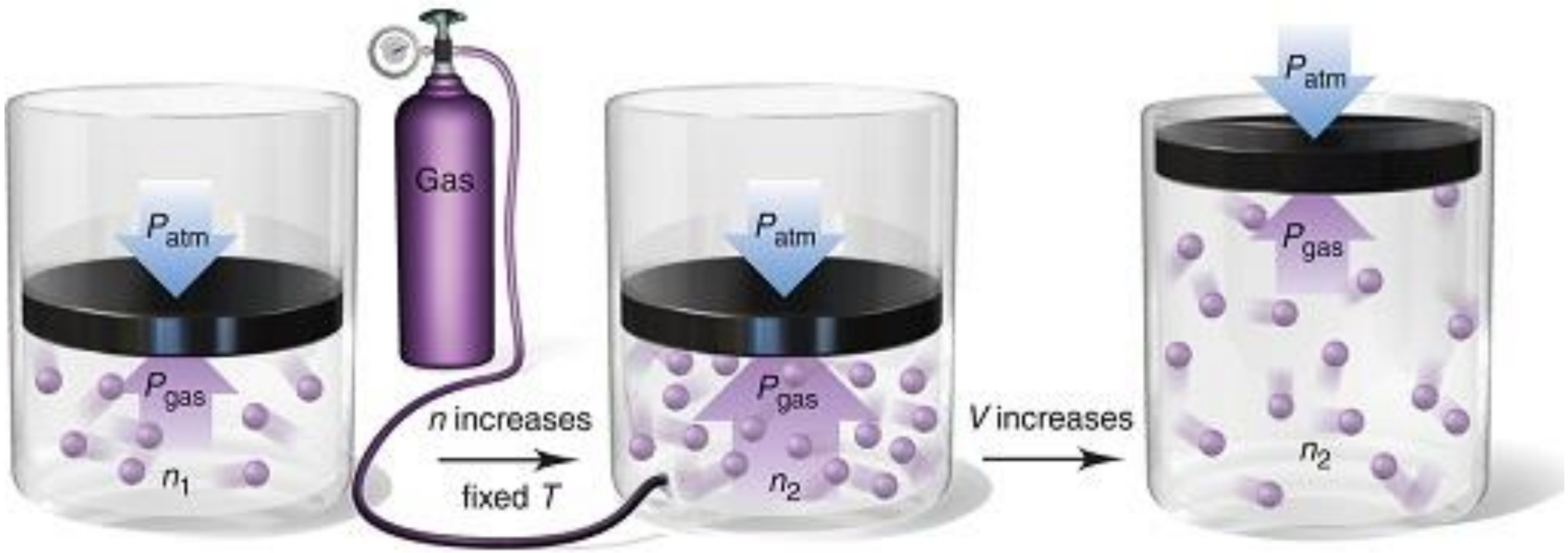
- At constant volume, the pressure exerted by a fixed amount of gas is ***directly*** proportional to its absolute (Kelvin) temperature.

$P \propto T$ **or** $\frac{P}{T} =$ **constant** **or** $\frac{P_1}{T_1} = \frac{P_2}{T_2}$

Avogadro’s Law

- At fixed temperature and pressure, the volume occupied by a gas is ***directly*** proportional to the number of moles of gas.

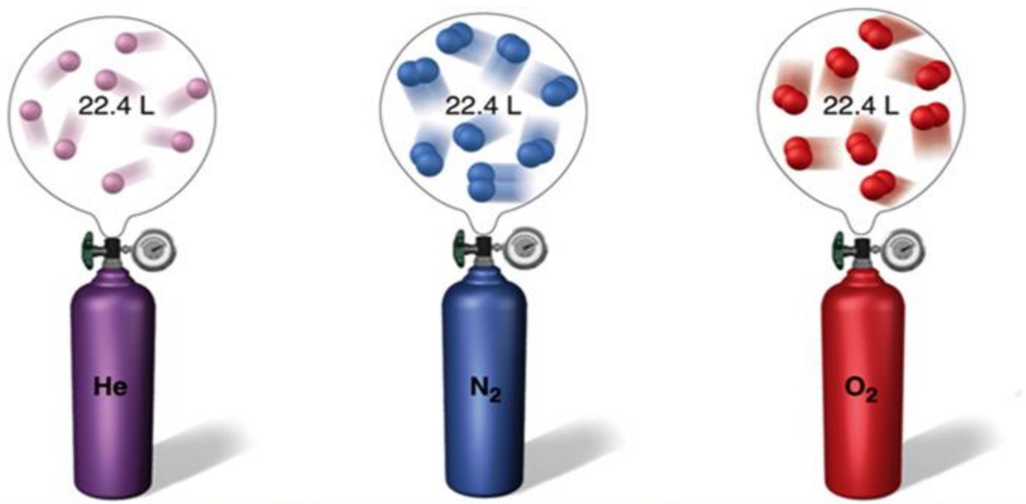
$$V \propto n \qquad \text{or } \frac{V}{n} = \text{constant} \qquad \text{or } \frac{V_1}{n_1} = \frac{V_2}{n_2}$$



Important Derivative of Avogadro's Law

- At fixed temperature and pressure, equal volumes of ***any*** ideal gas contain equal numbers of particles (or moles).

- The volume of **1 mol** of an ideal gas at **standard temperature and pressure (STP)** is **22.4 liters. STP** specifies a pressure of **1 atm (760 torr)** and a temperature of **0° C (273.15 K)**.



n = 1 mol	n = 1 mol	n = 1 mol
P = 1 atm (760 torr)	P = 1 atm (760 torr)	P = 1 atm (760 torr)
T = 0°C (273 K)	T = 0°C (273 K)	T = 0°C (273 K)
V = 22.4 L	V = 22.4 L	V = 22.4 L
Number of gas particles = 6.022×10^{23}	Number of gas particles = 6.022×10^{23}	Number of gas particles = 6.022×10^{23}
Mass = 4.003 g	Mass = 28.02 g	Mass = 32.00 g
d = 0.179 g/L	d = 1.25 g/L	d = 1.43 g/L

The COMBINED Ideal Gas Law

1) Boyle's Law: *PV* = constant

2) Charles's Law: $\frac{V}{T} = \text{constant}$

3) Pressure Law: $\frac{P}{T} = \text{constant}$

4) Avogadro's Law: $\frac{V}{n} = \text{constant}$

$$\frac{PV}{nT} = \text{constant} = \text{R}$$

$$\Downarrow$$

$$\frac{P_1V_1}{n_1T_1} = \frac{P_2V_2}{n_2T_2} = \text{R}$$

$$\text{R} = \frac{PV}{nT} = \frac{1\ \text{atm} \times 22.414\ \text{L}}{1\ \text{mol} \times 273.15\ \text{K}} = \frac{0.0821\ \text{atm·L}}{\text{mol·K}}$$

R is called the Universal Gas Constant

Sample Problem 5.3

A balloon is filled with 1.95 L of air at 25ºC and then placed in a car in the sun. What is the volume of the balloon when the temperature in the car reaches 90ºC?

$V_1 = 1.95 L$

$T_1 = (25 \cancel{°C} + 273.15) K = 298.15 K$

$V_2 = ?$

$T_2 = (90 + 273.15) K$

$= 363.15 K.$

$$\frac{\cancel{P_1} V_1}{\cancel{n_1} T_1} = \frac{\cancel{P_2} V_2}{\cancel{n_2} T_2}$$

<u>Charles's Law:</u>

$$\frac{1.95 L}{298.15 K} = \frac{V_2}{363.15 K}$$

$$V_2 = \frac{1.95 L \times 363.15 \cancel{K}}{298.15 \cancel{K}} = \boxed{2.38 L}$$

Sample Problem 5.4

A scale model of a blimp rises when it is filled with helium to a volume of 55.0 dm^3. When 1.10 mol of He is added to the blimp, the volume is 26.2 dm^3. How many **more grams of He** must be added to make it rise? Assume constant *T* and *P*.

$V_1 = 26.2\ dm^3 = 26.2\ L$

$n_1 = \underline{1.10\ moles}$

$V_2 = 55.0\ dm^3 = 55.0\ L$

$n_2 = ?$

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$

or, $$\frac{26.2\ L}{1.10\ moles} = \frac{55.0\ L}{n_2}$$

$$\Rightarrow n_2 = \frac{55.0\ \cancel{L} \times 1.10\ moles}{26.2\ \cancel{L}} = \underline{2.31\ moles}$$

$\Delta(\#\ moles) = n_2 - n_1$

$= (2.31 - 1.10)\ mol$

$= 1.21\ moles$

$$1.21\ \cancel{moles\ He} \times \frac{4.00\ g\ He}{1\ \cancel{mol\ He}} = \boxed{4.84\ g\ He}$$

Sample Problem 5.6

A steel tank has a volume of 438 L and is filled with 0.885 kg of O_2. Calculate the pressure of O_2 at 21ºC.

$V_1 = 438 L$

$P_1 = ?$

$T_1 = (21°C + 273.15) K$

$= 294.15 K$

$n_1 = 0.885 \cancel{kg\ O_2} \times \frac{1000 \cancel{g\ O_2}}{1 \cancel{kg\ O_2}} \times \frac{1\ moles\ O_2}{32.00 \cancel{g\ O_2}}$

$= 27.7\ moles\ O_2$

$\frac{P_1 V_1}{n_1 T_1} = R$

$\frac{P_1 \times 438L}{27.7\ moles \times 294.15K} = 0.0821$

$P_1 = \frac{0.0821 \times 27.7 \times 294.15}{438L}$

atm

$\boxed{P_1 = 1.53\ atm}$

Sample Problem 5.7

The piston-cylinder is depicted before and after a gaseous reaction that is carried out at constant pressure. The temperature is 150 K before the reaction and 300 K after the reaction. (Assume the cylinder is insulated.)

Which of the following balanced equations describes the reaction?

1) $A_2(g) + B_2(g) \rightarrow 2AB(g)$
2) $2AB(g) + B_2(g) \rightarrow 2AB_2(g)$
3) $A(g) + B_2(g) \rightarrow AB_2(g)$
4) $2AB_2(g) \rightarrow A_2(g) + 2B_2(g)$

$$\frac{\cancel{P_1}\cancel{V_1}}{n_1 T_1} = \frac{\cancel{P_2}\cancel{V_2}}{n_2 T_2}$$

$$\frac{1}{n_1(150K)} = \frac{1}{n_2(300K)}$$

$$\frac{n_2}{n_1} = \frac{150\cancel{K}}{300\cancel{K}} = \frac{1}{2}$$

$\boxed{\text{Equation 3}}$

Sample Problem 5.9

An organic chemist isolates a colorless liquid from a petroleum sample. She places the liquid in a pre-weighed flask and puts the flask in boiling water, causing the liquid to vaporize and fill the flask with gas. She closes the flask and reweighs it. She obtains the following data:

Volume (*V*) of flask = 213 mL   *T* = 100.0ºC   *P* = 754 torr

mass of flask + gas = 78.416 g   mass of flask = 77.834 g

Calculate the molar mass of the liquid.

$V = 213\,mL = 0.213\,L$

$P = 754\,torr = \frac{754}{760}\,atm = 0.990\,atm$

$T = 100.0^\circ C = 373.15\,K$

$m = (78.416 - 77.834)\,g$

$= 0.582\,g$

$\frac{PV}{nT} = R$

$\frac{0.990\,atm \times 0.213\,L}{n \times 373.15\,K} = 0.0821$

$n = \frac{0.990\,atm \times 0.213\,L}{0.0821 \times 373.15\,K} = 0.0069\,moles$

$\#\,moles = \frac{mass}{MM}$

or, $0.0069 = \frac{0.582\,g}{MM}$

$MM = \frac{0.582\,g}{0.0069\,mol}$

$= 84.3\,g/mol$

Sample Problem 5.12

What volume of H_2 gas at 765 torr and 225ºC is needed to react with 35.5 g of copper(II) oxide to form pure copper and water?

$$\boxed{CuO(s) + H_2(g) \longrightarrow Cu(s) + H_2O(l)}$$

$$P = 765\ \text{torr} = \frac{765}{760}\ \text{atm} = 1.01\ \text{atm} \qquad \frac{PV}{nT} = R$$

$$T = 225^\circ C = 498.15\ K \qquad n = 0.446\ \text{mol}$$

$$35.5\ \cancel{g\ CuO} \times \frac{1\ \cancel{mol\ CuO}}{79.55\ \cancel{g\ CuO}} \times \frac{1\ mol\ H_2}{1\ \cancel{mol\ CuO}} = 0.446\ mol\ H_2$$

$$V = \frac{nRT}{P} = \frac{(0.446\ \cancel{mol})(0.0821\ \frac{L \cdot \cancel{atm}}{\cancel{K\ mol}})(498.15\ \cancel{K})}{1.01\ \cancel{atm}} = 18.06\ L$$

$$\boxed{18.1\ L}$$

Partial Gas Pressure and Mole Fraction

Mixtures of Gases

- The pressure exerted by each gas in a mixture is called its ***partial pressure***.

- **Dalton's Law of partial pressures** states that *the total pressure in a mixture is the sum of the partial pressures of the component gases.*

$$P_{total} = P_A + P_B + P_C$$

- The ***partial pressure*** of a gas is proportional to its ***mole fraction***.

$$P_A \propto n_A \qquad \frac{P_A}{P_{total}} = \frac{n_A}{n_{total}}$$

Sample Problem 5.10

In a study of O_2 uptake by muscle at high altitude, a physiologist prepares an atmosphere consisting of 79 mole% N_2, 17 mole% $^{16}O_2$, and 4.0 mole% $^{18}O_2$. The total pressure of the mixture is 0.75 atm to simulate high altitude. Calculate the **mole fraction** and **partial pressure** of $^{18}O_2$ in the mixture.

$$\text{Mole fraction} = \frac{n_{18O}}{n_{total}} = \frac{4}{100} = \boxed{0.04}$$

$$P_{^{18}O_2} = \text{Mole fraction} \times P_{total}$$

$$= 0.04 \times 0.75 \text{ atm}$$

$$= \boxed{0.030 \text{ atm}}$$

Related Problems

Problem 5.24

A weather balloon is filled with helium to a volume of 1.61 L at 734 torr. What is the volume of the balloon after it has been released and its pressure has dropped to 0.844 atm? Assume that the temperature remains constant?

Ans: 1.84L

Problem 5.26

A sample of sulfur hexafluoride gas occupies 9.10 L at 198°C. Assuming that the pressure remains constant, what temperature (in °C) is needed to reduce the volume to 2.50 L?

Ans: − 144°C

Problem 5.36

You have 357 ml of chlorine trifluoride (ClF_3) gas at 699 mmHg and 45°C. What is the mass (in g) of the sample?

Ans: 1.16 g ClF_3

Thank you.
Any Questions?